

Selenium management for Alberta coal mines: state of practice review

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EXECUTIVE SUMMARY

The Alberta Government has recently convened the Alberta Coal Policy Committee (the committee) to collate and analyze public, regulatory, and industry input on the province's long-term approach to coal development. The committee will make recommendations to the Minister of Energy in the latter part of 2021. Water quality concerns have focussed on elevated selenium in water courses downstream of metallurgical coal mines. Selenium management, an important environmental consideration for Alberta's Rocky Mountain metallurgical coal mining sector, is the topic of this state of practice review.

Selenium is a naturally-occurring metalloid in bedrock, with properties similar to those of sulphur. When oxidized, it can be leached by precipitation and groundwater, seeping through rockpiles from both coal and metal mines, notably from those in the Canadian Rockies. In certain chemical forms, selenium can be biomagnified in receiving waters, where it has the potential to affect reproduction and development of aquatic birds and fish. Elevated selenium in drinking water can also affect humans directly and through water used for agriculture, however, this is less of a concern relative to ecological risk. In Canada, coal-mining effluents, and their environmental effects, are regulated stringently, both provincially and federally.

Since 1995, selenium has been identified as a significant chemical of concern in water exiting coal mines in British Columbia and Alberta. Guidelines for water quality have been developed and significant effort has been devoted to understanding the impacts of selenium, with a focus on measures to limit its loading in receiving waters downstream of mines. Background concentrations of 1–2 µg/L are common in the region, and – depending on the level of mitigation – concentrations are often one to two orders of magnitude higher downstream of existing mine rockpiles. The vast majority of the selenium is released from mine rockpiles (mining landforms built by drilling and blasting the bedrock above and between coal seams). The volume of mine rock is typically 10 times the volume of mined coal. The mine rock is loaded and hauled into permanent rockpiles that are typically 50 to 400 m high and can cover many square kilometres. Mine rock is also used to backfill mined-out pits.

Because of the potential for selenium to accumulate in fish and aquatic birds in and around receiving waters, management of selenium from historical (closed), active, and new mines is critical for environmental protection. Research and development and ongoing commercialization of selenium-management strategies and technologies over the past 30 years has produced a wide range of practicable technologies that are available to all coal-mine operators. The technology readiness level of these technologies varies. Many are operating at a commercial scale, though only some can be considered “proven technology.” Research, development, and commercialization of these selenium management technologies continues at a fast pace.

The preferred and emerging strategy for selenium management is a comprehensive, multi-disciplinary design process that uses a combination of multiple lines of defence or a ‘multi-pronged’ approach (using many different technologies together) and the observational method — both of which are routinely employed in, for example, dam construction and operation). The strategy involves a combination of clearly-defined selenium targets in receiving environments,

avoidance (minimizing the mined rock with particularly high selenium content), source control (limiting the production and mobility of oxidized selenium in mine rockpiles), water management strategies (keeping clean water clean), and mitigation (the collection and treatment of waters with elevated selenium).

This review describes and evaluates more than 23 strategies and technologies for selenium management. Most mines will require most of these technologies as part of an integrated system. The observational method (similar to adaptive management) will be employed, with contingencies fully developed for all known upset conditions, and a monitoring program that allows for timely and effective use of these varied contingencies.

Eight case studies of selenium management at existing and proposed mines in Alberta and British Columbia are presented. These studies illustrate that selenium management is a central activity for active mines and central to the planning and design of new mines. For regions and watersheds in which there has been historical mining, selenium concentrations in receiving environments are typically elevated, requiring new mines to minimize selenium loads leaving their respective site, and for active mines to retrofit their landscapes. Existing mines cannot usually meet provincial water quality guidelines for aquatic life; site-specific water quality objectives are typically required.

For new and existing mines, the most promising technology is the use of semi-passive saturated mine rock backfill reactors (saturated rock fills; SRF), where mine rock is deposited into mined-out pits in such a way as to form a saturated zone at the base that precipitates selenium. Biogeochemical theory, laboratory experiments, and some full-scale field situations suggest that selenium in effluent can be reduced to remarkably low concentrations (i.e., $< 5 \mu\text{g/L}$). So while this technology is operating at a commercial scale, this report does not consider it to be “proven technology” until more publicly-available data confirms good performance.

The other technology being proposed for new mine rock landforms involves expanding the size of the suboxic zone that forms within these rockpiles, limiting oxygen entering or moving within the landform through a combination of low air-permeability internal structures, using coarse coal reject (CCR) and / or mine tailings in strategic layers within the landform, and placing cover systems and water diversions on the plateau and slopes of the landform. Observations at mines internationally, and numerical modelling, indicate promising results with this approach.

The evidence presented in this review indicates that mines can manage selenium through a combination of focused multidisciplinary design source control, water diversions, and mitigation measures, although the reliability of such a system has not been fully demonstrated at any active mines. Because at least low selenium loadings are likely for every mine, even with successful implementation of selenium management, the cumulative effects of historical mining (where applicable) and new mining must be fully considered — to a much greater degree than is presently addressed in permitting. For positive outcomes and general acceptance, experience has shown the need for strong and close collaboration among proponents, Indigenous peoples, local communities, and regulatory bodies, each of whom are part of the solution and each of whom will share the benefits and the liabilities of the reclaimed mining landscapes.

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1.0 INTRODUCTION AND BACKGROUND

Recently, concerns have been raised by the public and the media regarding impacts of coal mining in Alberta. One of these concerns relates to the potential degradation of water quality due to selenium that leaches from mine rock. To provide the Alberta Coal Policy Committee (AG 2021) with state-of-the-science / state-of-practice information regarding selenium management, the objective of this report is to review the selenium issue in metallurgical (steel-making) coal mining in Canada, with a specific focus on the province of Alberta.

The report provides broad context regarding: selenium effects, assessment, regulations, mitigation strategies, and treatment technologies. Case studies and examples — in Alberta and British Columbia — are also provided to illustrate the current state of practice and the opportunities for improved selenium management.

The report argues that selenium can be well managed in Rocky Mountain coal mining, but requires a diligent, defence-in-depth strategy involving a number of approaches, including: selective mining and selective handling; advanced mine planning; cover systems and landform grading; source control; and water management, collection, and treatment with either passive, semi-passive or active water treatment technology as viable contingencies. Many of these technologies are already operating at a commercial scale, but most have room for improvement. Only a few are judged as “proven technology” for Rocky Mountain Coal mining based on publicly available information.

Even with good design and operational measures, there will be residual selenium loads entering the receiving streams; careful consideration of all mining activities in each watershed is a critical component of the full cumulative effects assessment. There is a need for strong collaboration among mining companies, First Nations peoples, the local community, and regulatory bodies, to successfully manage the cumulative effects of selenium in the environment.

This report was written by Guy Gilron, MSc, RPBio, ICD.D and Gord McKenna, PhD, PEng, PGeol, two independent consultants with expertise in this discipline, retained by Patrick Landry (Director of Engineering) of the Cabin Ridge Project. Any opinions expressed herein are those of the authors. Appendix A provides information about the authors.

1.1 Terminology

The following definitions and associated descriptions are required for a full understanding of the concepts used in this review.

There are two main types of coal. **Metallurgical coal** is used to make steel and comes in two subtypes: **coking coal** is used in the production of metallurgical coke, which is then heated in a blast furnace to produce liquid iron; this coke acts as a source of carbon, which is essential in the reduction of oxygen in iron ore during the purification process to produce steel, while **pulverized coal injection coal** has sufficient levels of carbon and latent heat to enable it to be injected into the blast furnace to replace a portion of the coke. Most metallurgical coal is

exported. **Thermal coal** is used to generate electricity. Most thermal coal is consumed by mine-mouth powerplants.

Selenium is a metalloid, similar to sulphur, that is found in some rocks and soils (SAPSM 2010). In Rocky Mountain coal mines, selenium is associated with trace quantities of pyrite and other sulphides in sedimentary bedrock (Hendry et al. 2015). Selenium is released from some mine rockpiles¹ by oxidation (i.e., the interaction of oxygen, water, and microbes). While it is an essential trace element, it is potentially toxic at higher concentrations and bioaccumulates through aquatic food webs. The two main effects are skeletal deformities and reproductive failure in fish and aquatic birds. At much higher concentrations, there can be impacts on direct human consumption (drinking water), and agriculture (irrigation and livestock watering).² Selenium is an unusual element in that it can occur in a large number of oxidation states, some of which are essentially immobile in mine rock or sediment. **Selenate** (SeO_4^{2-}), an oxidized form of selenium analogous to sulphate, is particularly soluble in water.

Two main benchmarks are used to evaluate the effects of coal effluent discharge on water quality. These are as follows:

- **Aquatic life guidelines** are set for both freshwater and marine systems, and are meant to be applied in ambient receiving water bodies (e.g., lakes rivers, streams, oceans) upstream from or beyond the edge of the mixing zone. Canadian examples include: national Water Quality Guidelines set by the Canadian Council of Ministers of the Environment (CCME)³ and federal environmental quality guidelines set by Environment and Climate Change Canada (ECCC)⁴, as well as Provincial Aquatic Life Guidelines set by Alberta Environment and Parks.⁵
- **Effluent discharge limits** are applied in two different ways when included in operation-specific permits⁶: at “end-of-pipe” final discharge points (FDPs) from tailings facilities and sedimentation ponds; or, downstream of the mine operations and FDPs. These environmental compliance points (ECPs) are determined at the federal level (proposed *Coal Mining Effluent Regulations* [CMERs]) and provincial level (e.g., in Alberta under the *Environmental Protection and Enhancement Act* [EPEA]⁷). Figure 1 illustrates the differences between these two kinds of benchmarks.

¹ Mine rockpiles have historically been referred to as waste rock dumps or spoil piles – the terminology is slowly evolving.

² https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/water-quality-guidelines/approved-wqgs/bc_moe_se_wqg.pdf

³ <https://ccme.ca/en/summary-table>

⁴ <https://www.canada.ca/en/health-canada/services/chemical-substances/fact-sheets/federal-environmental-quality-guidelines.html>

⁵ <https://open.alberta.ca/dataset/5298aadb-f5cc-4160-8620-ad139bb985d8/resource/38ed9bb1-233f-4e28-b344-808670b20dae/download/environmentalqualitysurfacewaters-mar28-2018.pdf>. GoA 2018.

⁶ This paradigm is being proposed as part of the federal *Coal Mining Effluent Regulations*, since not all coal mining operations monitor effluents at FDPs.

⁷ <https://open.alberta.ca/dataset/c7c021be-54c1-48fb-9bc4-eaf7b1a1afff/resource/dbdad77-891c-43ca-b4a5-3c6d037c5775/download/industrialwastewaterlimits-jun1999.pdf>

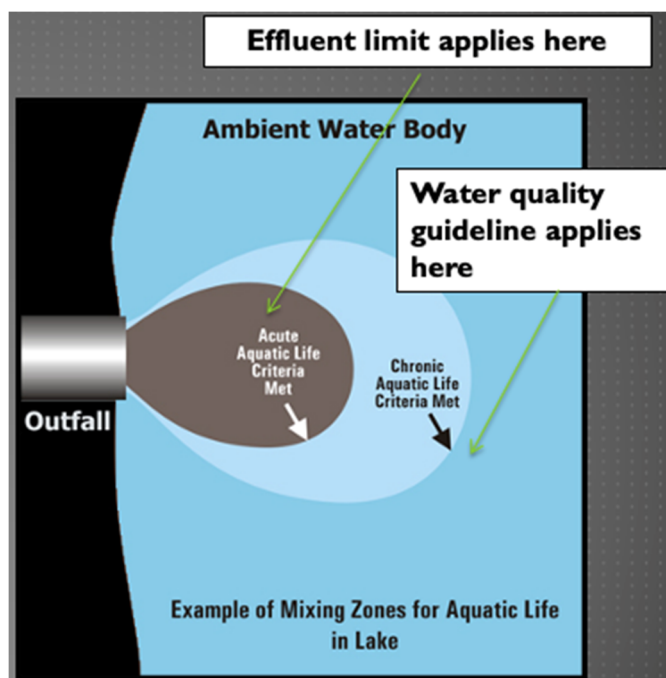


Figure 1. Difference between aquatic life guidelines and effluent discharge limits and how they are applied.⁸

Landform design is an emerging, integrated, multidisciplinary process to successfully reconstruct mine land. It allows industry, regulators, and communities to manage costs and risks, minimize liability, and produce progressively reclaimed landscapes with confidence and pride (McKenna 2002; LDI 2021).⁹ It is being employed at mines internationally, including some coal mines in Alberta and British Columbia. The **observational method** (Peck 1969) has been adapted for use in landform design and allows designers to incorporate uncertainty in the design and construction of mining landforms and landscapes. It is similar to, but pre-dates, traditional adaptive management¹⁰ (Walters 1986; BCFR 2011). The observational method involves designing for the most likely conditions, identifying all potential failure modes, providing well-developed contingency plans should landscape performance be less than required, and monitoring performance to be able to implement contingency measures in a timely manner. This is a common approach to the design of large dams in Alberta and around the world. It is similar to adaptive management, but more robust. Landform (and dam) designers incorporate a **multiple-lines-of-defence strategy**, in which redundant systems are employed to reduce risk from hazards — for example, in the case of selenium management, including water management, selenium source control, and collection and treatment in the same design.

⁸ Modified from United States Environmental Protection Agency (http://water.epa.gov/scitech/swguidance/standards/mixingzones/pop_pic3.cfm)

⁹ <https://landformdesign.com/pdf/LDI-PositionPaper2021.pdf>

¹⁰ Adaptive management is a common feature of regulations and mining permit applications but has a poor track (Allen and Gunderson 2011) record and is often simply a trial and error strategy (Kwasniak 2010; CEMA 2012). The observational method is very similar to adaptive management but includes predefined contingency measures.

1.2 An overview of the coal mining sector in Canada

1.2.1 Canada's contribution to global coal production

Coal production in the world is dominated by China, followed by India, the US, Indonesia, and Australia. A total of 90% of coal produced globally is used for power generation (i.e., thermal coal). Coal-fired power plants generate 37% of the world's electricity and coal furnaces produce more than 70% of the world's steel. The Canadian coal sector is responsible for more than 42,000 direct and indirect jobs in Canada and \$2.6 billion in wages and salaries.

1.2.2 Canadian coal mines

There are currently 24 coal mines (18 of which are currently in production, 6 of which are in suspension), located in Western Canada and 1 in Nova Scotia. It is estimated that about 25 projects are currently in various stages of regulatory review.

The majority of Canada's coal is extracted by open-pit or strip mining. With open-pit mining, reclamation of ex-pit mine rock piles is conducted concurrently, and the open pits are either backfilled with mine rock or become pit lakes (e.g., Sphinx Lake in Alberta (Brinker et al. 2011)). These mines are generally reclaimed to wildlife habitat using native trees, shrubs, and grasses. With strip mining, reclamation (mainly to farmland) is carried out concurrently with mining using agronomic species.

1.2.3 Geographic variation in Canadian coal mines

There are three types of coal mines in Canada, based on geographic variation:

- Mountain mines (Alberta, British Columbia) have a complex geology with significant faulting; they are generally structurally complex; they comprise coal seams dipping at steep angles of up to 80°. They are mined using open-pit mining methods. The extracted coal is exported offshore, primarily via west-coast terminals.
- Prairie mines (Alberta, Saskatchewan) are generally characterized by relatively simple geology; they comprise seams that are generally flat-lying, with some seam splitting and minor undulations and mined by strip-mining methods. The extracted coal generally serves mine-mouth power stations.
- Atlantic mines (Nova Scotia) have thick coal seams with simple geology.

1.3 Metallurgical coal mining in Alberta

This section provides the current status of coal mines/projects in the province. Table 1 provides details pertaining to coal mining projects in Alberta.

Table 1. Coal mining projects in Alberta: Exploration, advanced projects, and active mines (2021)

Type	Project	Location	Information
Exploration projects	Aries	Nordegg (Category 2)	Bituminous metallurgical coal exploration project No current exploration activities
	Blackstone	Nordegg (Category 2)	Bituminous metallurgical coal exploration project Approved January 2020
	Cabin Ridge	N of Coleman (Category 2)	Bituminous metallurgical coal exploration project Approved October 2020
	Chinook	Coleman (Category 4)	Bituminous metallurgical coal exploration project Approved June 2020
	Elan South	N of Blairmore (Category 2)	Bituminous metallurgical coal exploration project Approved May 2019
	Isolation South	N of Blairmore (Category 2)	Bituminous metallurgical coal exploration project Approved July 2019
Advanced projects	Grassy Mountain	Blairmore (Category 4)	Proposed bituminous metallurgical coal mine Joint Review Panel pending.
	Tent Mountain	Crowsnest Pass (Category 4)	Proposed bituminous metallurgical coal mine Proponent preparing EIA
	Vista (Phase 2) Expansion	Hinton (Category 4)	Proposed bituminous thermal coal mine expansion A joint review panel review will be required
Active mines	Cheviot (Cardinal River)	Hinton	Bituminous metallurgical coal export Mining ceased in 2020; began operations in 1968
	Coal Valley	Hinton	Bituminous thermal coal export Began operations in 1973
	Grande Cache	Grande Cache	Bituminous metallurgical coal export Began operations in 1970s
	Genesee	Warburg	Sub-bituminous thermal coal Domestic electricity Began operations in 1980
	Highvale	Wabamun	Sub-bituminous thermal coal Domestic electricity Began operations in 1969
	Paintearth / Vesta	Forestburg	Sub-bituminous thermal coal Domestic electricity Began operations in 1978/1922
	Sheerness / Montgomery	Hanna	Sub-bituminous thermal coal Domestic electricity Began operations in 1979/1914
	Vista	Hinton	Bituminous thermal coal Export Began operations in 2019

Source: <https://www.alberta.ca/assets/documents/energy-coal-in-alberta-factsheet.pdf>

The Rocky Mountain coal mines include several different coal fields of Jurassic, Cretaceous, and Paleogene (Tertiary) ages (Smith et al. 2021). Coal is mined from the Mist Mountain Formation (in southwest Alberta, southeastern BC, and west-central Alberta), the Coalspur and Gates Formations (in west-central Alberta), and the Gething and Gates Formations in northeastern BC. Coal seams are both overlain and separated by interbedded layers of sandstone, siltstone, and mudstone. These sedimentary rocks have variable, but typically elevated, levels of selenium. The bedrock is typically overlain by glacial materials, some of which are stockpiled or direct hauled for reclamation material (see Paquin and Brinker 2011).

Open-pit coal mining involves: blasting to fragment the bedrock; loading and hauling the coal for processing; and loading, hauling, and dumping the non-coal layers for permanent storage in mine rockpiles. The volume of mine rock is typically about 10 times that of the extracted coal. The resulting rockpiles are typically 50 to 400 m high, can cover many square kilometers, and comprise angular sandy, gravel-sized particles (with numerous boulders), and are highly porous. They may be end-dumped (tipped from the top of the rockpile to form long angle-of-repose slopes), or built in layers (“bottom-up construction”). Hendry et al. (2015) provide rockpile profiles in the Elk Valley, indicating digestible selenium concentrations in the mine rock of 1 to 6 mg/kg (with an average of ~3 mg/kg) which mimic selenium concentrations in bedrock.

1.4 Environmental regulatory and permitting framework

Canada’s coal mines operate within a complex and stringent regulatory environment. Mines are subject to up to 16 federal mining industry acts and regulations, many of which relate to coal mines, and laws, regulations and permits at provincial and territorial levels. Appendix B provides an overview of the environmental regulatory and permitting framework for the coal sector in Canada.

In addition, the industry operates according to high reclamation standards. Mining companies are legally responsible for reclaiming land disturbed by mining activities. Alberta’s Mine Financial Security Program (MFSP) is designed to manage liability by collecting financial security from the mine owners. The level of security is based on the years of remaining coal reserves.¹¹ Because the program is not fully funded during a mine’s operational period, the public shares the liability for closure, should the mine close unexpectedly and/or if the company defaults.

1.5 Coal-mining effluents

This section provides an overview of the composition of coal-mining effluents, parameters of concern, the management of water and effluent at coal mines, and water quality and effluent limits applied in Canada (and beyond).

1.5.1 Chemicals of concern in coal-mining effluents

The following parameters have been observed to be elevated in coal-mining effluents and receiving environments: pH, total suspended solids (TSS), nitrate, sulphate, and selenium. These parameters are the focus of mitigation measures and water treatment at most coal mines in Canada. Calcite precipitation downstream of mine rock piles is also a concern (MacGregor et al. 2012).

While other parameters have been identified as elevated (other than on an occasional and/or site-specific basis; e.g., cadmium), a comprehensive review of effluent data obtained from 19 Canadian coal mines over a period of four years did not support the inclusion of any of these parameters in effluent monitoring programs at coal mines (Borealis Environmental 2014). This

¹¹ <https://www.aer.ca/regulating-development/project-closure/liability-management-programs-and-processes/mine-financial-security-program>

report focuses exclusively on selenium and selenium management. Selenium was identified as a significant chemical of concern in water exiting Rocky Mountain coal mine areas in 1995 (Berdusco et al. 2000).

1.5.2 Water and effluent management and application of guidelines and limits

- **Water management**

At coal mines, water is generally controlled via surface and groundwater interception; specifically, water is directed to settling ponds for removal of suspended sediments, and then released or used on mine roadways for dust control. Export mines have coal-washing plants. At some mines, water is recycled, with little being released. In the mountain/foothills mines in British Columbia and Alberta, while most tailings water may be recycled/re-used, most mine wastewater is released, subsequent to treatment (if required, based on exceedances of one or more of the above-mentioned parameters).

- **Effluent management**

Effluent management at coal mining operations is generally conducted using conventional means such as diversion and settling, and treated effluent is discharged into the receiving environment, after meeting permit / approval conditions / requirements. Provinces are responsible for permitting the development of new coal mines and coal mine expansions (as discussed above); facilities are subject to provincial requirements for effluent release.

Discharge limits are generally derived on a site-specific basis, and are generally consistent in approach within jurisdictions. But this is not always the case in Alberta and British Columbia. While the coal sector has always been subject to section 36 of the federal *Fisheries Act*, there is no specific federal regulation for coal-mining effluent, similar to the regulations for metal and diamond mines.¹² ECCC is currently developing and proposing federal regulations for the coal sector (i.e., *CMERs*); these regulations — when they take effect — will include limits for the abovementioned parameters (with the exception of sulphate).

- **National vs site-specific guidelines/objectives and limits**

With respect to water quality, monitoring and reporting of major parameters (including acute lethality toxicity testing with rainbow trout and *Daphnia magna* (water fleas)) in effluent discharge is conducted in accordance with provincial permits/approvals. National aquatic life guidelines (e.g., CCME, ECCC) and effluent limits (e.g., provincial permit-specific limits, federal (proposed) *CMER* limits) do not always reflect the variability of the geography and geology of the different regions (i.e., mountains, foothills, prairies) in which various coal mines are located.

Site-specific considerations (e.g., modifying and confounding factors for parameters such as selenium and sulphate) are key to managing the effects of effluent on water quality near coal mines.

¹² The current regulations for these two mining sectors are the *Metal and Diamond Mining Effluent Regulations* (2018).

In some Canadian provinces, selenium guidelines¹³ near industrial operations have recently been modified on a basin/watershed- or site-specific basis into water quality objectives to address specific parameter issues, such as high background concentrations, lower targets to protect impaired systems, and cumulative impacts concerns. These types of objectives are often specified in discharge permits, together with associated monitoring requirements. As a result, it is appropriate to derive and establish:

- Site performance objectives for developing mines; and/or,
- Site-specific water quality objectives or science-based environmental benchmarks (SBEs; BCMOE 2016) for operating mines.

1.6 Alberta's 1976 Coal Policy and the current situation

This report was commissioned in response to recent activities related to the Government of Alberta's rescindment, reinstatement, and subsequent solicitation of public feedback of Alberta's 1976 Coal Policy. The government announced the formation of a five-member Coal Policy Committee to consult the public on future coal mining policy for Alberta. Its report is due in November 2021.

1.7 Previous compilations

Numerous reports and peer-reviewed articles have been published over the past 15 years by groups and researchers tasked with summarizing and evaluating selenium management options. This report draws heavily on the work of several of these studies, including:

- Selenium management options (Chapman 2005)
- Water treatment technologies / Alberta Environment Water Research Users Group (Sobolewski 2006)
- Environmental management criteria / Ecometrix (Fitzgerald and Nicholson 2008)
- Selenium in the Elk Valley / Elk Valley Selenium Task Force (EVSTF) (Pumphrey and Gilron 2009)
- Selenium management strategies / Strategic Advisory Panel on Selenium Management (SAPSM 2010, 2012)
- Evaluation of the Effects of Updated Selenium Water Quality Criteria on Water Management in North America: Status of Selenium Criteria Development. [In conjunction with the American Petroleum Institute and the North American Metals Council – Selenium Working Group] (GEI/Windward/Borealis 2018).

¹³ Water quality guidelines are meant as "flags" for potential effects/risk of elevated concentrations. An elevated concentration does not necessarily indicate risk, *per se*, since water quality guidelines are derived to be appropriately conservative. Where water quality meets a guideline, further work is seldom warranted. Where guidelines are exceeded consistently, and/or continue to increase, additional work is required, including the derivation of a suitable site-specific water quality objective, which can then become incorporated into compliance criteria.

- Review of selenium treatment technologies (Golder Associates (2020) and earlier and ongoing work by the North American Metals Council – Selenium Working Group including Review of available technologies or the removal of selenium from water (CH2MHill 2010; 2013) (NAMC-SWG)¹⁴

Three additional useful sources of broad information on selenium and selenium management are:

- Selenium 101 (Ohlendorf 2011)
- Elk Valley Water Quality Plan (Teck 2014)
- Permit 107517 Environmental Monitoring Committee (Teck 2019)

¹⁴ <https://www.namc.org/selenium.html>

2.0 SELENIUM FATE AND EFFECTS

2.1 Selenium overview

Selenium is a naturally-occurring metalloid. It is a trace essential element required by all living organisms. The distribution of selenium in the Earth's crustal surface is uneven; this results in some geographic regions being low in selenium, while others contain elevated levels (see Figure 2 (North American variability of selenium)). Soils containing elevated selenium concentrations (i.e., “seleniferous” soils) are present in many areas of the world.

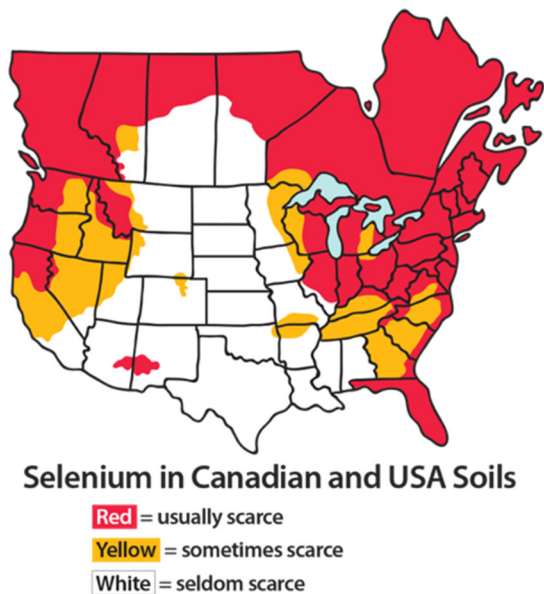


Figure 2. Qualitative distribution of selenium in North American soils (modified from NRC, 1983)

Selenium is a critical micronutrient that is routinely applied as a supplement for plants (soil amendments) and livestock in agriculture. It is also used as a dietary supplement for humans in selenium-deficient areas and is included in many daily multivitamin formulations.

Some ecosystems can adapt to seleniferous situations, while others cannot. Therefore, selenium resources need to be managed accordingly — in some regions, due to geographic scarcity and in others, because of potential for impacts on wildlife.

Selenium exists in multiple forms (or chemical “species,” mainly inorganic) in natural environments. Each of these species exhibits unique properties, which adds to the challenge of managing selenium in the environment. It behaves almost like a group of compounds — the range / profile of a given selenium species may or may not be similar in different ecosystems.

2.2 Selenium effects in the aquatic environment

Sulphur and selenium are in the same periodic table group, and are considered “analogue elements,” in that they share characteristics due their chemical similarities (Figure 3). This

analogue property is important in the formation of the two sulphur-containing amino acids, cysteine and methionine, in which sulphur is normally taken up in their formation. When selenium is taken up instead of sulphur, the two seleno-amino acids are known as seleno-cysteine and seleno-methionine. Amino acids are the building blocks of proteins in biological systems of plants and animals, and any changes resulting from the replacement of sulphur by selenium are important.

phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453
arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904
antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90

Figure 3. Relative position of selenium and sulphur in the periodic table of elements.

Seleno-amino acids — the organic forms of selenium — can be incorporated into living organisms, as they mimic their sulphur analogues. However, they differ from their sulphur analogues in some ways due to selenium's higher atomic weight. Seleno-amino acids therefore also behave differently when they are incorporated into biological systems (in particular, during reproduction and development of egg-laying vertebrates; see below).

Trace amounts of selenium are essential for general metabolism and, in particular, mitigate the impact of oxidative stress¹⁵ in living organisms. For this reason, some people ingest selenium as a supplement and some farmers administer it to livestock. However, when selenium concentrations taken up by certain organisms are too high, seleno-amino acids can be incorporated into proteins that would normally contain sulphur, altering their function in the animal body. When this happens under certain conditions, effects have been observed in aquatic vertebrates that lay eggs (i.e., fish, aquatic birds). Under certain physical and chemical conditions, selenium can bioaccumulate in the tissues of these animals, and can become problematic for higher trophic level organisms in the food web — the organisms that consume fish, aquatic birds, and possibly amphibians (Janz et al. 2010).

Aquatic food web bioaccumulation generally follows a path from water to algae (single-celled plants that grow on rocks or are suspended in rivers and lakes), which are then consumed by

¹⁵ A disturbance in the balance between the production of reactive oxygen species (free radicals) and antioxidant defenses.

small, bottom-dwelling invertebrates. These are, in turn, eaten by fish and aquatic birds (Figure 4). At each level of the food web, selenium can become more concentrated in body tissues; however, this does not always happen in a consistent or predictable manner. Under conditions that result in greater selenium bioaccumulation, sufficiently high concentrations in fish and aquatic birds can cause adverse effects on the development of skeletal structures, the capacity to reproduce properly, and the survival of offspring.

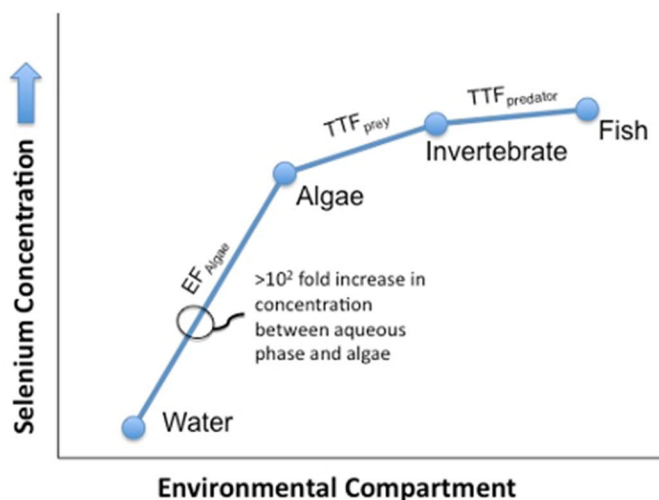


Figure 4. Bioaccumulation of selenium in aquatic food webs (Stewart et al. 2010).

2.3 Impacts of selenium on the aquatic environment

Fish and other aquatic species in many areas can be exposed to both natural and human-generated sources of selenium. Documented effects of elevated selenium on fish (and aquatic birds), in particular those that have been used to derive water quality guidelines, are based primarily on laboratory tests. However, the population impacts of selenium on wild fish reported 30 to 40 years ago (Cumbie and Van Horn 1978; Woock and Summers 1984) have not been observed (Gilon et al., *in review*). The earlier population-impact scenarios occurred in contained reservoirs into which coal ash leachate from power plants was discharged. The amounts and concentrations of selenium in these scenarios were extremely high (i.e., > 100 µg/L¹⁶) compared with concentrations in coal-mining effluents discharging from present-day operations.

While selenium guidelines and criteria used to evaluate water quality have been established for potential adverse effects, a consistent correlation has not yet been established between selenium concentrations in water and associated impacts on aquatic organisms. Ecosystems and their characteristics are diverse, and selenium behaves differently in different environments under a variety of chemical conditions. The impact of selenium is wide-ranging, but the extent of

¹⁶ µg/L is akin to ppb = parts per billion.

impact depends on multiple variables, many of which are not yet well understood. This is the result of the complex mechanisms by which selenium can enter an aquatic food web, and the challenges involved in effectively measuring selenium in its many forms in the environment over time and in different locations.

In waters with constant inputs of high selenium concentrations, most of the selenium accumulated at higher trophic levels (e.g., fish) is initially taken up from the surface water to algae. This initial step is also the most variable in the bioaccumulation process (Figure 4). The magnitude of bioconcentration by algae varies a great deal and depends on the type of environment (i.e., fast-moving, or slow-moving waters), the communities of algae present (and associated species diversity), concentration and speciation of selenium in water, and other modifying factors (e.g., concentration of sulphate). The potential for adverse effects (toxicity) also depends on organism sensitivity, which varies greatly among fish and aquatic birds.

2.4 Current North American regulatory guidelines/criteria for selenium

Regulatory values for selenium water quality assessment in North America range from 0.8 to 5 µg/L for the protection of freshwater aquatic life (Table 2) and from 10 to 50 µg/L for drinking water (the latter guideline values vary internationally) (Table 3). Because fish show the greatest sensitivity to selenium, the focus for evaluating selenium is typically on aquatic life guidelines / criteria (mainly fish-based), rather than human health / drinking water criteria.

Table 2. Summary of current aquatic life water quality guidelines/criteria in regulatory jurisdictions in North America

Jurisdiction	Guideline/criterion (µg/L)	Reference	Notes
United States (federal)	fast-moving waters: 3.1 slow-moving waters: 1.5	U.S. EPA (2016)	Decreased from previous draft criterion of 5 µg/L (for all water bodies). Now distinguishes between lentic and lotic systems.
Kentucky (state)	5	Payne, Kentucky Energy and Environment Cabinet (2013)	Applied using a tiered approach; fish tissue concentration measured and evaluated when water selenium limit is exceeded.
Montana (Lake Koocanusa)	0.8	MT DEQ (2020)	Recently approved by US EPA Region 8.
Canada (national) (CCME)	1	CCREM (1987)	Derived using outdated approach (i.e., based on field data from lake studies). Federal revision in 2021 only addressed fish and bird egg tissue.
British Columbia (provincial)	2	Beatty and Russo (2014)	The guideline document was updated, but retained the previous value of 2 µg/L. The 2014 guidelines added alert concentrations, interim values, and fish tissue values.
Alberta (provincial)	2	N/A	Adopted from British Columbia (above). Rationale is based on statistical comparison between BC and US EPA approaches.

Table 3. Summary of international drinking water quality guidelines (modified from Gilron 2012)

Jurisdiction	Previous/current (µg/L)	Revised / notes
US EPA	50 (previously, 10)	Scientific correspondence indicates it could be as high as 200 µg/L No change to date
South Africa	Class 1 – 20 Class 2 – 50	No change to date
Australia, New Zealand, EU, WHO	10	WHO provisional guideline elevated to 40 µg/L (WHO 2011)
Canada	10	50 µg/L (HC 2014)
British Columbia	10	Revision; retained 10 µg/L

Due to recent developments in the Elk Valley with respect to selenium in the receiving watershed, and a focus on selenium exceedances, management plans, and water treatment, there has been a significant regulatory focus on selenium discharges, from coal mines in particular¹⁷. Scientific research on the ecological effects of selenium affords specific attention to understanding the implications of selenium concentrations in fish and aquatic bird tissue compared with established and emerging regulatory benchmarks (e.g., back calculation of fish tissue concentrations at which effects are observed to aqueous guidelines and limits (DeForest et al. 2017)).

The values derived by various regulatory authorities are considered appropriate for ambient or pristine waters. However, effluent limits are generally used to benchmark water quality at the end-of-pipe (i.e., final discharge point) at industrial facilities (in this case, coal mines). These effluent limits are generally higher than the ambient criteria, and are generally derived from a back calculation from the ambient guidelines and criteria to acknowledge what is referred to as mixing zones downstream of effluent discharges (Figure 1).

2.5 Selenium monitoring and assessment

Because selenium chemistry and toxicology are complex, understanding selenium behaviour is key to predicting and managing environmental outcomes. Given an understanding of selenium dynamics and impacts related to various compartments of aquatic ecosystems (water, sediment, algae, invertebrates, egg-laying vertebrates, in addition to toxicity-modifying factors such as sulphate), much attention has been paid to the development of monitoring and assessment programs that inform environmental decision making and regulatory programs, including environmental effects monitoring.

¹⁷ Teck Resources coal mines in the Elk Valley are currently being regulated for selenium (via the *Elk Valley Water Quality Plan*, under an area-wide provincial order). (Teck 2014)

The NAMC-SWG has commissioned comprehensive research and development on this topic. Ohlendorf et al. (2011) provides details of the major components of monitoring and assessment programs. Similar work has also been developed by the USEPA related to fish population monitoring and evaluation (USEPA 2016) and, in particular, drafting implementation guidance for the application of selenium criteria (USEPA, 2017a,b). In Canada, British Columbia has also developed similar guidance (Beatty and Russo, 2014).

2.5.1 Evaluation of selenium in coal mine project development

The various stages of coal mine project development include components that require consideration of selenium dynamics, exposure and risk as follows:

- Environmental assessments
 - Environmental baseline studies
 - ▶ Geochemistry – “source terms” from mine rock
to understand the origin of the selenium
 - ▶ Hydrology/limnology – climate, design events and flow
to understand aqueous selenium dynamics as water leaves the mine site
 - ▶ Hydrogeology – groundwater flow and quality
to understand water balance on the mine site
 - ▶ Water quality – receiving environment and predicted effluent quality
to understand overall water balance and water management
 - ▶ Fish/aquatic biota – ecological receptors
to understand valued components that require protection
 - Effects assessments
 - ▶ Water balance, aquatic effects assessment (including assimilative capacity)
 - ▶ Ecotoxicity evaluations / modelling / risk assessment
 - ▶ Human health
- Permitting and management plan(s)
 - Water management plans
 - Selenium management plans
 - Environmental management systems

3.0 SELENIUM MANAGEMENT, MITIGATION, AND TREATMENT

This chapter summarizes selenium management methods, most of which are in commercial use, although some are still at the research or development phase. Table 4 provides a summary of the technology readiness levels (see Appendix D for more detail).

3.1 Selenium management considerations, mine, and facility design considerations

Selenium management is incorporated into mine design. This section provides a list of 23 technologies and strategies grouped in four major themes – avoidance, source control, diversions, and mitigation. Successful selenium mitigation, and successful reclamation in general, requires a clear vision, goals, objectives, and design criteria among the mine owners, Indigenous peoples, local communities, and regulators (see Swanson et al. 2011; Ansah-Sam et al. 2016; LDI 2021). It is common for mines to evaluate various “suites” of technologies using a multi-criteria decision analysis to select the best-suited technology(ies) for their site.

Most modern mines are designed for closure, and planning usually begins before mining begins and continues throughout the mine life and beyond. (LDI 2021). Progressive reclamation is important to selenium management and is generally carried out throughout a mine’s life by maximizing the potential use of backfilling (for both aboveground and underground mines) and, in some provinces, the creation of end-pit lakes (strip mines and open-pit mines).

3.2 Selenium management strategies / technologies for mining

As part of initial mine planning during project development, various technologies and strategies to manage selenium (see Table 4) are evaluated and incorporated as needed to manage performance, risk, and cost. NASA (2017) provides a simple technology-readiness level (TRL) scoring system that has been adapted for use in other mining technology development programs and is adapted here for selenium management in Rocky Mountain mines (see Appendix D for details).

The scoring is qualitative and is based on publicly-available information (some technologies are likely more advanced than indicated). Some technologies are more advanced elsewhere in the international mining industry, but have not been applied specifically to selenium management. Most are simple and supported by science; however, the attrition rate for technology development of specific technologies is generally high (CTMC 2012); unproven technologies come with risks, even for simple mining technologies. Implementation of selenium technologies is costly and requires ongoing conscientious leadership and close regulatory and community oversight over many decades at every mine. Some technologies are more suitable for greenfield sites (especially controlling internal structures of rockpiles), others for sites with existing mine rock landforms built before selenium was known to be an issue (e.g., active water treatment). Many technologies, such as diversions and water collection systems, will be employed at all Rocky Mountain coal mines.

Based on the TRL scoring applied to selenium management, most of these technologies have been demonstrated at a commercial scale, although most also have significant room for improvement. No one mine has demonstrated the full use of selenium management for the whole site over its entire mining life cycle. The general strategy is to minimize the generation, liberation, and mobility of selenium, and to capture and treat any that is produced.

This strategy calls for using a well-developed monitoring system (see below) to confirm that the selenium management, the mining landscape, and the receiving streams are performing as intended, and to determine whether pre-planned contingency measures are needed to ensure ongoing acceptable performance.

Table 4. Technology readiness levels (based on NASA (2017) scoring method)

Type	Technology	Rocky Mountain coal mine selenium management technology readiness level TRL			
Mining methods	Underground mining	4			
	Selective mining	8			
	Selective handling	7			
Source control	Siting mine rock dumps	8			
	Foundation preparation	7			
	Controlling internal structure	7			
	Controlling bacteria (temporary)	7			
	Cover systems	7			
	Blending mine wastes / codisposal	8			
	Add reducing agents / enhanced microbial reduction	4			
	Submergence	8			
	Schedule and timing	4			
Water management	Understanding baseline conditions	8			
	Diversions	9			
	Covers to shed water	4			
	Lotic discharge	9			
	Rockdrains	9			
	Surface water hydrology	8			
	Managing seepage and groundwater	8			
Mitigation	Surface and groundwater collection	6			
	Saturated rock backfill reactor	7			
	Biochemical reactors	7			
	Pit lakes	7			
	Active water treatment	7			
			Research	Dev	Comm

3.2.1 Underground mining

Historically, underground coal mining was common in Alberta. However, efficiencies in material handling and equipment mean that most mines now are either strip mines (on the prairies) or open-pit mines (in the mountains). A benefit of underground mines is that the volumes of mine rock, the largest source of selenium, are small and therefore easier to manage. Mine planners compare underground and open-pit mining methods as part of initial lease development planning.

New underground mining is unlikely to be economically viable compared with open-pit mining unless selenium cannot be properly managed without restricting operations to underground mining. In either case, selenium management is required, but would likely be much simpler for underground mining.

3.2.2 Selective mining for avoidance of selenium

Selective mining involves adjusting mine plans and operations to avoid mining rock with undesirable attributes, such as: ores that are difficult to process, rock that is physically weak, or (as is important to our case here), rock with poor geochemistry. Complete avoidance is seldom practical, but often mines have opportunities to leave problem materials “in the wall” unmined.

At mines for which selenium is a concern, drill cores are assayed for selenium and the data are interpreted geologically and included in the geological database and geology block model. Some formations are essentially selenium-free, but those associated with the coal seams (e.g., sandstones, siltstones, and mudstones) typically have moderate to high levels of selenium. Some units or zones have considerably higher selenium concentrations and are evaluated for selective mining with the goal of reducing the mass of selenium in mine rockpiles that might be leached — for example, at the Wolverine Mine in northeastern BC. At mines where there is little difference in selenium concentrations among the various units, selective mining is not practical.

3.2.3 Selective handling

Selective handling is a mine waste management practice in which wastes with different properties are handled differently. For example, mine rock with high selenium levels could be placed in backfilled pits where it will be saturated (thereby minimizing selenium oxidation), or different waste streams can be blended or layered to improve the performance of the mine waste landform. Combining mine rock and CCR together or in layers can also be part of a source-control strategy, as discussed below.

3.3 Selenium management technologies for source control

People involved in assessing the risks of leachates from mine waste often refer to “source, pathway, and fate” (e.g., INAP 2014) and develop strategies to disrupt this chain of events.

Source control is a common mine waste management technique for reactive mine rock and tailings to minimize the production and transport of chemicals of concern (COCs) from the mine waste, essentially tying up the COCs within the mine waste, either permanently or such that they release at an acceptably slow rate. For selenium, source control involves a combination of

limiting the inflow of oxygen and water into the mine rock, restricting the movement of water and especially oxygen within the mine rock pile, and – in some cases – creating conditions in which the oxidized selenium is quickly reduced and precipitated by layers within the mine rock pile.

This section describes a “multiple-lines-of-defence” strategy for employing multiple methods for source control as illustrated in Figure 5.

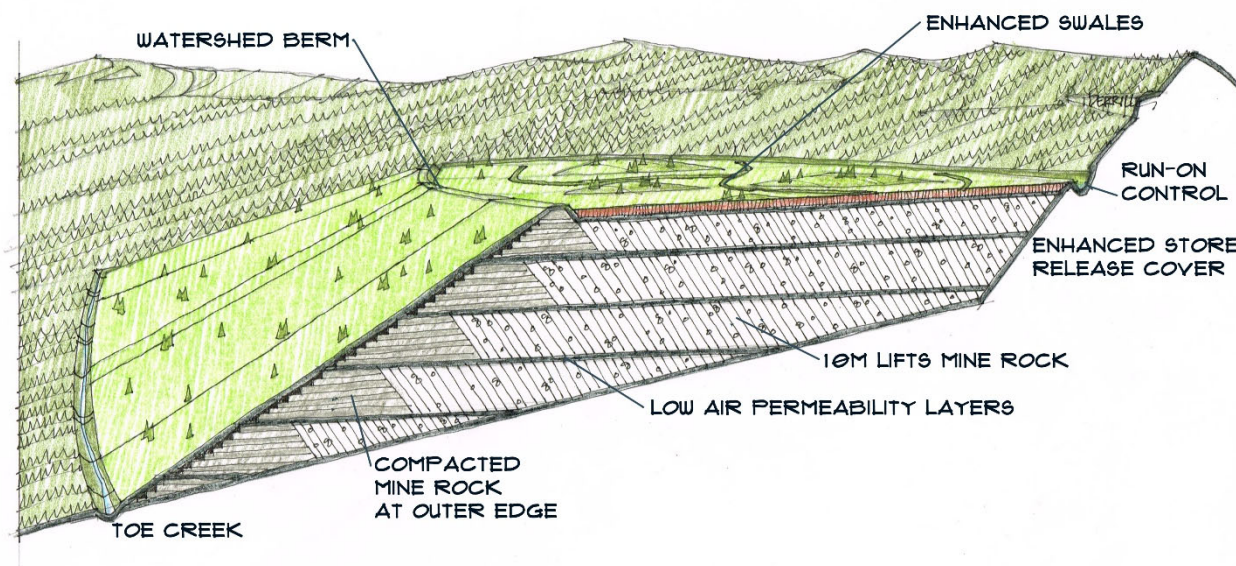


Figure 5. Controls to create suboxic zones in mine rockpiles as selenium source control (Derrill Shuttleworth illustration; adapted from North Coal¹⁸).

3.3.1 Source control strategy

The strategy for selenium source control is to limit the ingress of water (i.e., run-on water onto the mine rock pile, net percolation through the plateau or slopes, and groundwater coming from the hillslope), limiting the ingress of oxygen to the mine rock during construction and after placement of the cover system, and limiting the movement of oxygen within the pile.

Testing has demonstrated that large coal-mine rockpiles can form a seasonal suboxic zone, in which oxygen levels are less than about 5% (compared with 21% in the air) due to the oxidation of carbon and pyrite within the mine rock (see Figure 6, Day et al. 2012, and Barbour et al. 2016). Rates of selenium oxidation in suboxic zones are greatly reduced compared with areas that are well oxygenated. For piles in which this air transport is restricted through the use of internal structures within and covers on the mine rock, some field observations and numerical modelling indicate that the suboxic zone grows to include most of the mine rock (Meiers et al. 2018; O’Kane et al. 2019); this would greatly reduce the amount of selenium oxidation (and mobility) for the rockpile as a whole.

¹⁸ <https://northcoal.ca/michel-coal-project/>

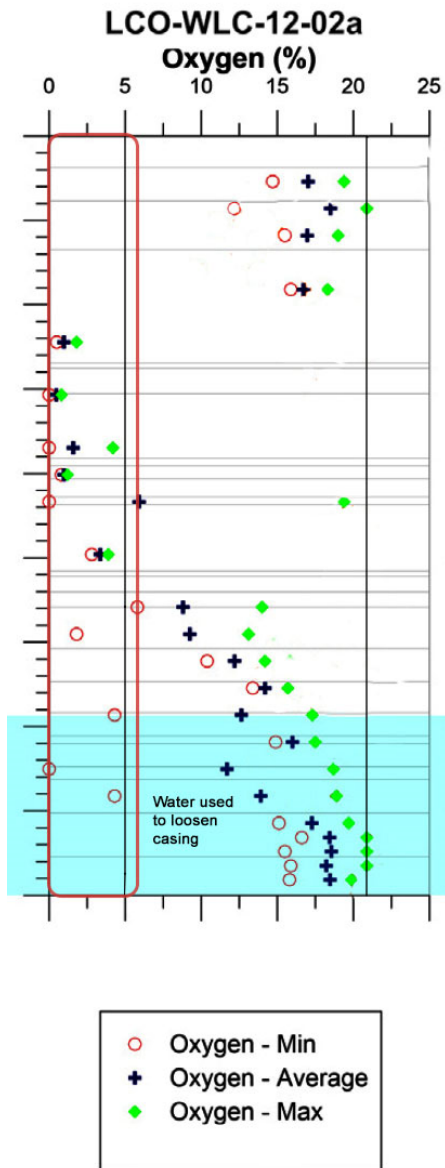


Figure 6. Seasonal oxygen depletion in a mine rockpile (adapted from Barbour et al. 2016).

Where there is permanent submergence of mine waste, there is almost no oxygen, and the selenium cannot oxidize. This is an excellent method of source control, where practical. Permanent saturation as source control is a different, but complementary, strategy to using a saturated zone in a saturated mine rock backfill reactor to precipitate mobilized selenium.

There is limited oxygen penetration in CCR landforms, which are finer than mine rock landforms and have low selenium concentrations and low oxygen in the pore waters / pores. Kennedy et

al. (2015) report suboxic conditions ($< 6\%$ oxygen¹⁹) in a CCR pile to a depth of 10 m. There may be an opportunity to strategically place CCR or tailings in mine rock pile landforms (either in layers or intimately mixed with mine rock²⁰) as a source control strategy, as discussed below.

Most of the rest of this section is focused on mine rock, as CCR and tailings present lower risks of selenium impacts²¹. For mine rockpiles, various source control methods are examined by landform designers, and are generally used in combination, as illustrated in Figure 5.

3.3.2 Siting of mine rockpiles

Mine rock haulage and placement are typically one of the greatest costs for coal mines. Planners work to keep hauls short with minimal changes in elevation, and minimal dozer work to spread the dumped mine rock. Often the most economical and environmentally-friendly location for a mine rock pile is in a mined out area (an “in-pit pile”), but it typically takes many years to open enough pit space to start backfilling with mine rock. As a result, one or more “ex-pit piles” are used for permanent storage of mine rock in a mine’s early years.²² Minimizing the volume and footprint of ex-pit piles is an important mine planning constraint. Planners also select the location of ex-pit rockpiles based on land tenure, foundation conditions, groundwater conditions, downstream impacts, and effects on fish and wildlife.

For Rocky Mountain coal mines, the siting of rockpiles includes consideration of source control and other management methods for selenium. The overall pit shells are largely dictated by the ore body and strip ratios, but the sequence of mining is adjusted to allow for early placement of mine rock, the formation of saturated zones, and a stable pit lake. Ex-pit sites with favourable conditions for run-on controls (typically, diversion channels in bedrock), high piles (to minimize footprint), and the ability to collect selenium-enriched waters, are part of the design and decision-making process.

Siting involves numerous trade-offs, and often only limited information is available for the first design and the start of mining. Two major uncertainties stand out: the presence of fractures or faults that might transmit seepage water into or out of the mine rock, and the presence of historical underground workings, most of which are poorly mapped and may also serve as conduits for seepage. Accurate predictions regarding performance of the bedrock and surficial materials in controlling leakage are often limited by geological uncertainty or the presence of underground workings, important factors in design.

¹⁹ The definition of “suboxic” does not yet seem to be formally defined for Rocky Mountain coal mines.

²⁰ If the goal is to create suboxic conditions in tailings or CCR (or mixtures with mine rock), the layers need to have sufficiently low air permeability and sufficient thickness to create a usefully large suboxic zone. However, if the goal is to impede the flow of oxygen within a rockpile, thin layers may suffice.

²¹ Each mine still evaluates the potential and impact of selenium loading from these materials and will employ strategies in this section to manage selenium, as necessary.

²² Options for placing mine rock in the mined-out pit of another mine are seldom practical (mainly due to haul distances, timing, and land tenure). As some mines, regulators require mines move mine rockpiles and tailings into the mined-out pit after closure, essentially doubling mine rock haulage costs.

3.3.3 Foundation preparation

Foundation preparation for ex-pit mine rock pile geotechnical stability is a routine practice, and may involve clearing standing water, snow and ice, and soft ground. It often involves logging and may involve grubbing. For this practice, designers may require placement of internal mine rock drains (to transmit clean or mine-influenced waters) and use compacted clay or membrane-type liners to control seepage out of the mine rockpile. Liners have numerous design considerations including: puncture resistance, longevity / service life, and geotechnical stability. In some cases, toe drains will be designed to avoid becoming conduits for oxygen.

For cases involving capture and treatment of selenium-enriched water, interceptor pumping wells may be installed, and bentonite cut-off walls or grout curtains may be employed as discussed below. These may be installed prior to mine rock placement. Foundation preparation is a routine activity at all mines.

3.3.4 Cover systems and topography for controlling water and oxygen ingress

Designers employ two main technologies to enlarge the size of the suboxic zone to engulf most of the volume of mine rock in a pile by limiting gas transport into, and within, the mine rock. They use covers (see Pearce et al. 2017; Ayres 2008, 2018) and internal structures, as noted in the next section.

As illustrated in Figure 5, cover systems envelop the mine rock in both in-pit and ex-pit mine rock landforms. The plateau and slopes of the mine rock are contoured (see Schor and Gray 2007) and a cover system of layers of compacted geomaterials (potentially with a geomembrane) is constructed. The system has many functions; here we focus on limiting oxygen ingress into the mine rock. Ideally, the only opportunity for oxygen ingress through the cover is diffusion, but in practice, there will be advective transport through defects (especially cracks) in the cover. Limiting oxygen ingress causes the suboxic zone to grow and reduces seasonal changes in oxygen levels, severely slowing selenium oxidation within the mine rockpile.

The cover also helps limit water percolation into the mine rock, which will transport oxidation products (in particular, selenate, but also sulphate and other soluble salts and ions). The additional water requiring treatment increases costs.

The use of cover systems is a routine part of mine waste management and reclamation practice internationally. MEND (2012) and INAP (2017) are two key documents that provide design direction. Use of instrumented test covers is a common (and necessary) part of design for local conditions and aids in performance predictions.

3.3.5 Controlling internal structure for mine rockpiles

As indicated above, mine rockpiles are constructed by end dumping of large lifts to produce a predictable internal structure of long and continuous coarse and fine layers and lenses parallel to the pile face, typically with a coarse boulder lag at the base. Unfortunately, this structure encourages the flow of oxygen that can literally whistle through a rockpile. The mechanics of the

“chimney effect” (i.e., the heating of air as it passes through oxidizing mine rock), the role of wind and changing barometric pressure, and daily and seasonal cycles of gas transport are all well documented (see for example Birkham and O’Kane 2020). Similarly, the pattern of water flow and oxidation of mine waste within the pile are all well understood.

Disrupting the preferential flow of gas through the piles, which is part of the strategy to maximize the extents of the suboxic zone, is reasonably well documented and understood; however, the technology is only occasionally employed in the mining industry. “Building from the bottom up” — building in lifts 5 to 20 m high (rather than end dumping from high slopes above) can enhance geotechnical stability and reduce re-grading costs. This common technique avoids the long-dipping coarse mine rock zones and limits the chimney effect. Air permeability can be greatly reduced by ensuring that the top of each lift is finer-grained. This can be achieved by selective placement of mine waste or more commonly by allowing a traffic / running surface to develop (by repeated trafficking of haul trucks) and especially if this layer is moist. These techniques can also be employed to limit oxygen ingress from the pile plateau and to limit oxygen ingress through rock drains or other drainage elements at the base of the pile (see Barritt et al., 2016).

Early attempts at controlling oxygen ingress in mine rockpiles (often promising anoxic conditions) were largely unsuccessful and have given this method of controlling gas a poor reputation. A frequent failure mode was the development of large cracks in the covers (often due to settlement deformations or slope instability), allowing oxygen ingress and unconstrained by internal structures. More recent work, with higher levels of design, have indicated success, but demonstration at the full landform scale appears lacking. A large (i.e., 200-hectare) geomembrane prototype trial is planned at Teck’s Greenhills Mine (Teck 2020).

3.3.6 Controlling bacteria

Considerable laboratory and field research has been conducted into use of biocides to control *Thiobacillus* bacteria that catalyze acid rock drainage in metal mines. These efforts generally have proven to be futile, as microbial communities evolved / re-established after a few months, particularly in the field. Such measures are unlikely to be any more successful when applied to long-term selenium source control.

However, enhancing the activity of selenium-reducing bacteria, particularly in saturated mine rock backfill reactors by the addition of carbon that is readily available for consumption, may be an important aspect of the design (Kirk et al 2017). Research suggests that a wide variety of carbon sources (from ethanol to molasses to manure) can be employed. Some carbon is already available to bacteria (largely through mudstones and coal in the mine rock), but whether these sources are sufficient is unknown. Carbon can be added: as a solid or sprayed as a fluid on each lift, using a watering truck or perhaps sprinklers; perhaps as a spray, to each truckload; injected through wells into constructed mine rockpiles; or, combined with captured process-affected water before it is added to saturated backfill for treatment. The efficiency of each method is evaluated, but to be effective, the carbon must reach the microbes (intimate contact).

It is important to note that the carbon additions mentioned above will also influence effluent water quality.

3.3.7 Adding reducing agents

Reducing agents that minimize selenium concentrations can be added to mine rockpiles during deposition or injected into the mine rock pile to precipitate selenium. For example, there has been considerable research into zero-valent iron (ZVI) (and other types of iron and other types of zero-valent metals (see Golder 2020)).

The use of reducing agents for selenium source control is backed by considerable laboratory experience, but is still in the early research stage.

3.3.8 Blending mine wastes

Coal mines produce a number of waste streams. Mine rock, CCR, and tailings²³ are the main streams of interest for selenium management. CCR and tailings deposits are typically associated with anoxic conditions and little selenium oxidation or release (see Siddique et al. 2007). The volume of CCR and tailings together amount to about 10 to 15% of the volume of mine rock (Dawson 1994) and varies from mine to mine. Combining these wastes with some of the mine rock may improve the performance of the mine rockpile by reducing gas permeability and transport, and it may also reduce water permeability (hydraulic conductivity).²⁴ The amended zones may help create localized reducing conditions, causing precipitation of the selenium, although this has yet to be demonstrated in the field.

Blending of mine wastes typically requires intimate contact among the different waste materials. This can be accomplished by placing the materials in layers and mixing them using extensive cross-ripping with a dozer. Other options involve combining the waste streams on a conveyor or using a pug mill for mixing, both of which are likely more expensive. Field tests to develop procedures and a program of quality control and quality assurance would be required.

Designers check that the blending of these mine wastes do not cause geotechnical instability, which is always a concern when there are finer-grained layers or zones within mine rockpiles or where water may build up within the mine rock pile (Dawson 1994). Some designers have expressed concerns about whether a mine rock pile containing tailings might cause the mining landform to be considered a tailings facility, which would trigger different levels of permitting and regulatory oversight. Discussion between the mine and the regulators can likely resolve this issue during the early planning stages.

Blending mine waste is a common activity at mines, especially those with acid rock drainage issues. Early research on blending often underestimated the need for intimate contact among materials, but these issues have largely been resolved. Blending mine wastes is common in the

²³ Some coal mines have a combined stream of CCR and tailings, often referred to as co-disposal.

²⁴ This reduction in permeability has little impact on the performance of selenium management for thin layers, but perched water may negatively impact geotechnical stability – a key concern for designers.

coal industry, notably for combinations of tailings and CCR, but blending with mine rock for managing selenium is in the developmental stage.

3.3.9 Submergence

Placing mine rock below the water table reduces selenium oxidation to very low levels. Designing pit backfilling to create a large, saturated zone is a common method to prevent oxidation. Flooding mine rock in a pit lake is another useful strategy. Creation of impoundments for flooding mine rock using dams is usually impractical in steep Rocky Mountain valleys, but it may be possible to build dam-like structures within mine rockpiles in cross-valley fills to create large, saturated zones that would submerge mine rock to create a suitable residence time for reducing reactions (Claridge et al. 2012). The practicality of such techniques has not been demonstrated and may only apply in limited situations. Designers typically go to great lengths to avoid creating dams that require perpetual monitoring and maintenance.

Designers need to demonstrate that any scheme that relies on submergence to prevent selenium oxidation is permanent, and that leaks through fractured bedrock or historical underground workings would not compromise such a system. Detecting leakage zones prior to construction would involve dedicated pit-wall mapping. Remediation of excessive leakage may be prohibitively expensive.

Submerging mine waste to limit oxidation is a mature technology internationally. It is perhaps the single most effective method of limiting acid rock drainage in mine rock and tailings and is backed by years of experience and a solid technical basis. It is also a commercial-scale technology for managing selenium production in coal mines.

3.3.10 Scheduling and timing of construction

During mine rock pile construction, much of the landform is exposed to precipitation (most of which percolates into the pile) and to nearly full atmospheric concentrations of oxygen, until the cover is installed (see O’Kane et al. 2019). The oxidation products produced during these initial years are likely to flush out of the mine rock and require treatment. This “first flush” needs to be anticipated in the volumetric water balance and water quality / treatment models. It may be possible to reduce the amount of construction oxidation by using layers with low permeability to gas during construction, but the efficacy of such systems has not been proven. The main method for control during this period is to construct an ex-pit mine rock pile as quickly as practical, using bottom-up construction (to limit pathways advective gas transport) and place an engineered cover system on the mine rock slopes during construction and on the final plateau as the pile reaches final height. This practice is starting to become more common at metal mines with acid rock drainage concerns. Scheduling and timing of mine rock placement and reclamation is routine at all mines.

3.4 Selenium management strategies and technologies for water management

This section provides an overview of the use of water management strategies and technologies as a part of selenium management systems.

3.4.1 Understanding hydrologic site conditions

Mountain hydrology is complicated. Mines typically have one or more on-site climate stations and instruments and sampling programs to monitor stream flows, groundwater pressures, and water quality in both surface water and groundwater systems. The understanding of these conditions is limited in the early days of mining and grows with time. It is complicated by extremes in elevation and the impact of winds on snow accumulation and melting rates, and by uncertainties in the geologic model.

Surface water hydrologists use surficial and bedrock geology information gathered during exploration and environmental impact assessment work to develop climate and surface water management models that can predict flows and design water management systems. Site hydrogeologists build on their understanding of the geology of the ore body, using block models to build site-scale and regional groundwater models to understand and predict flows. Water quality for both surface water and groundwater is also modelled, usually using simplified conceptual models, often with spreadsheets. Climate change, at least out to 100 years, is becoming a normal component of such modelling. A thorough understanding of surface water and groundwater is key to effective selenium management.

3.4.2 Diversions (keeping clean water clean to minimize treatment costs)

Surface-water diversion channels are used to intercept non-contact water runoff from upslope of the mine pit, process facilities, and mine rockpiles, and to minimize the volume of contact water that must be treated. This is often referred to as “keeping clean water clean.” Diversion channels in mountainous environments are usually dug into bedrock. They also cross talus fans and zones of fractured bedrock, both of which require measures to avoid unacceptably high water losses from the channels. Diversion channels have high capital and maintenance costs and are prone to blockage by debris flows, ice accumulation, and snow avalanches.

In some cases, the diversion channels can be moved on top of reclaimed mine rockpiles with the use of large, lined channels constructed as part of the cover system.

3.4.3 Managing surface contact water

Surface water that falls or runs onto the contact area must be managed operationally in the contact water system (sometimes referred to as the dirty water system). Mines have high levels of expertise in managing contact water and sediment control systems, including extensive ditching and large sedimentation ponds. The system is designed to run by gravity (water flowing downhill) where practical, supplemented by large pumps and pipelines as or when needed.

Storage and sedimentation ponds are designed to an environmental design flood, such as a fast snowmelt or rain-on-snow event for modest return period events. Flows that exceed this value are permitted to discharge to the receiving environment.

3.4.4 Managing seepage / groundwater

Seepage / groundwater management is common in coal mines, mainly to control stability and manage water in the open pits, and may be used to intercept contaminated seepage. Capture

and treatment of groundwater with elevated selenium concentrations is important to all selenium management, as discussed below. Plumes are common near the toes of rockpile landforms, through coarse alluvium or colluvial, coarse glacial till, in fractured or karstic bedrock, or through faults. Some leakage from sedimentation and holding ponds, from saturated mine rock backfill reactors, and from pit lakes is inevitable but designed to be low and manageable.

Contact-water seepage may appear as a seep (at the toe of the rockpile materials or downstream where the groundwater exists the surficial materials or bedrock to become surface water), or it may exit into the base of a creek or receiving environment with little visual evidence. Frequent sampling of narrow-diameter monitoring wells is used to detect selenium plumes as well as sampling of creeks. Development of a robust hydrogeological model is typically required as part of the selenium management process (e.g. Szmigielski 2015).

3.5 Mitigative measures and treatment systems

Even with a well-operated system of avoidance / selective mining, source control, and clean water management, some water will have elevated levels of selenium and may need to be collected and treated as described in this section.

3.5.1 Surface water and seepage water collection

Where selenium concentrations in contact water exceed discharge requirements, the water may be stored, or treated using semi-passive or active water treatment. Often the water is directed to a small sump (usually built using a combination of cut and fill) to allow pumping. Common strategies are to pump this contact water to a pit lake or to a saturated mine rock backfill zone once these facilities are established. Large holding ponds may be required in the short term. As noted above, in steep terrain it is difficult to build substantial storage for contact water outside of the open pit.

If needed, interceptor ditches and / or interceptor pumping wells can collect the selenium-affected water and pump it for storage and treatment. The capture efficiency of such seepage interception systems is typically less than 100%, sometimes much less, depending upon the nature and understanding of the hydrogeology. A low-permeability vertical cutoff wall (typically bentonite clay) constructed just downstream of the interceptor wells may be used to decrease bypass and increase capture efficiency. The interceptor system may be installed in advance, but more commonly is installed downstream of monitoring wells if a plume is detected. Often additional interception and monitoring wells are installed in phases to increase the capture efficiency over several years. The well systems require linear infrastructure such as pipelines, roads for maintenance, and power lines (and sometimes generators or substations) for operation.

The concentrations of various COCs (including selenium) in the contact water will vary widely with location and time, as will suspended sediment, bed loads, and water temperatures. This variability in influent water quality (and rates) has a significant impact on the performance of many treatment technologies and is accounted for in design. Large holding ponds can help reduce short-term variability of these influent waters.

3.5.2 Saturated mine rock backfill reactors

Saturated (or near-saturated) conditions provide the low-oxygen environment required for the reduction of selenium. In addition, storing mine rock under water-saturated conditions in pits that have been mined out eliminates exposure of submerged rock to oxygen, greatly limiting selenium oxidation and, therefore, the release of selenium to effluent discharged to the receiving environment.

Saturated rock fills have more recently been employed at coal mines in western Canada (e.g. Teck 2021) as a water management strategy to reduce elevated concentrations of selenium derived from the oxidation of minerals in coal and mine rock. Teck recently announced a doubling of the water treatment capacity at its Elkview operations.²⁵ Claridge et al. (2012) show how saturated zones may be constructed at the base of mine rockpiles in the thalweg of valleys.

3.5.3 Selenium treatment systems

Treatment systems that remove selenium from effluent prior to discharge into the receiving environment can be natural or engineered — or a combination of the two. These technologies range from passive (capitalizing on natural systems; e.g., wetlands), to semi-passive (a combination of both natural and engineered systems) to active (completely engineered systems; e.g., a treatment plant) systems. These systems can be based on physical, biological, or chemical transformations. Most programs apply a combination of mitigation measures and treatment technologies within the broader on-site water management system.

Selenium can exist in several chemical forms, just as nitrogen can exist as ammonia, nitrite, or nitrate. Each of the forms requires different processes for treatment. In coal deposits, selenium generally enters water as selenate and selenite. Some are more available to be taken up (i.e., accumulated in tissue) by aquatic organisms, and treatment methods generally aim to change the form of selenium. The type of water treatment needs to be matched to the type of selenium.

3.5.4 Semi-passive biochemical reactors, natural wetlands, and pit lakes

Conditions conducive to attenuating selenium (and other parameters, such as nitrate) can be enhanced through “bio-engineered” treatment techniques. Biochemical reactors are one such approach, in which an active or passive engineered structure supports the activity of microbes that help treat (i.e., remove or reduce) selenium loading / concentrations in wastewaters and effluents. Wetlands and pit lakes are often a viable alternative. As natural landscape features, they have significant advantages and are generally more aesthetically pleasing than engineered systems. However, they can be challenging, as they require management and monitoring to ensure effective removal of selenium from surface waters.

Passive and semi-passive treatment systems, such as wetlands and pit lakes (with demonstrated removal of selenium) are summarized in Table 5. These case studies indicate that selenium removal has been very effective at numerous sites in the US.

²⁵ <https://www.teck.com/news/news-releases/2021/teck-doubles-water-treatment-capacity-at-elkview-operations>

Table 5. Case studies of passive and semi-passive selenium treatment (from Martin et al. 2010)

Project	Location	System type	Treatment	Se concentration (µg/L)	
				Initial	Final
Chevron Marsh	San Francisco Bay, CA	Constructed surface-flow wetland	Adsorption/precipitation, biological uptake by plants, and volatilization to the atmosphere	20 to 30	< 5
Benton Marsh	Great Falls, MT	Engineered natural system comprising perennial and seasonal wetlands	Adsorption/precipitation, biological uptake by plants, and volatilization to the atmosphere	26	0.7
Sweetwater Pit	Sweetwater Country, WY	Pit lake	In situ removal through addition of nutrients and organic amendments	443	< 5
Anchor Hill Pit Lake	Gild Edge Mine, SD	Pit lake	Lime addition followed by in situ removal through addition of nutrients and organic amendments	20	< 1
Beal Mountain Mine Pit Lake	Butte, MN	Back-fill pit lake	In situ removal through addition of organic carbon during pit filling	42 to 47	2 to 3
Monticello Mill Tailings Site	Monticello, UT	Permeable reactive barrier	PRB using zero valent iron, in conjunction with impermeable funnel walls to funnel selenium-affected contaminated groundwater	18.2	0.1

Guidance and reviews of the international state of practice in pit-lake design, monitoring, and performance can be found in Castendyke and Eary (2009), CEMA (2012), McCullough et al. (2018), and Vandenberg (2018).

3.5.5 Active water treatment systems

Engineered treatment systems are used at various industrial operations, including coal mines. Examples are provided in Table 6; additional details pertaining to the range and effectiveness of these systems is provided in various reports including the State-of-Knowledge Treatment Technology Review (Golder, 2020).

Table 6. Examples of treatment technologies used for selenium removal from industrial effluents

Treatment	Examples
Filtration	Active treatment with filters can remove total selenium
Membrane separation	Reverse osmosis (active)
Resins	Ion exchange (active)
Biological reduction	Biochemical reactors (Active or Semi-passive), “brand name” units: <ul style="list-style-type: none">• Suez ABMet™• Frontier SeHawk®• Envirogen Fluidized Bed Bioreactor• Veolia AnoxKaldnes™
Biological oxidation	Moving bed bioreactors (Active) Aerated gravel beds (Active)
Chemical oxidation	Ozonation, peroxide, etc.
Photolysis	Photocatalysis, developmental, for reduction.
Electrochemical reduction	BQE Water Selen-IX™

3.5.6 Infrastructure

Semi-passive or active water treatment requires considerable long-term infrastructure, which may entail high capital and operating costs, and may affect land use and landscape performance goals. Moreover, financial assurance for ongoing operation of water treatment can be a significant financial burden on the operation (e.g., Equity Silver provides a useful case history (see Meintz 2018)).

Water treatment facilities are typically designed to run at a constant flux of an approximated number of cubic metres of water per day. In mountains, peak runoff typically occurs during snowmelt (freshet), requiring dams or ponds for storage of peak flows of contact water. Where steep slopes and high stream gradients, which are common in mountains, preclude incorporation of structures capable of storing the freshet, provision for annual bypass of untreated contact water to the receiving environment or the use of novel techniques for storing peak flows may be required, as discussed below.

These facilities require monitoring and maintenance, which need to utilize access roads and trails. Pumps require pipelines and electrical power. While operators typically need to be on-site, some sites can sometimes run remotely. A permanent on-site presence, with linear access, and the associated noise and light may disrupt wildlife and recreational values.

3.6 Monitoring methods

The monitoring of landscape performance before, during, and after operations is an essential component of the observational method and is also required for operations and for regulatory compliance (Fair et al. 2014). It is a central component of design and the backbone of the observational method, as outlined above.

The degree of selenium monitoring will vary site specifically and over time, but will necessarily include:

- determination of the selenium content of the ore body and adjacent rock (to support selective mining if employed)
- monitoring of stream flows and water quality in natural creeks and receiving water bodies and in the contact water system
- construction quality control monitoring of all aspects of mine rock pile construction including site preparation, material placement, re-grading, cover system placement, re-vegetation, and general landscape performance
- monitoring of groundwater levels and water quality
- monitoring of cover system performance (see Birkham et al. 2014)
- monitoring of water, gases, and other geochemistry within mine rockpiles (ex-pit, in-pit, in saturated mine rock backfill reactors)
- monitoring the efficacy of the semi-passive and active water treatment systems.

Such efforts will be part of the site-wide environmental monitoring programs to guide operations and compliance. Beyond physical monitoring, costs are closely tracked (as they will likely affect requirements for long-term financial assurance). A quality assurance program, to check that the quality control system is being well managed and determine whether the broader goals are being met, is a key element of selenium management.

3.7 Considerations for other mining landforms

Other mining landforms and landform elements (see Pollard and McKenna 2018) may play roles in selenium production. Each of these is formally addressed during all stages of mine / landform design.

Rock drains are often constructed at the base of mine rockpiles to channel upstream creeks or to manage seepage in rockpiles (Piteau 1997). They are coarse and have so little surface area that they are not thought to contribute meaningfully to selenium loading, but they do allow oxygen to enter the mine rockpiles and they can also readily transmit selenium-enriched water from the rockpiles.

CCR piles and tailings deposits, as noted above, do not seem to be sources of selenium oxidation as their fine-grained nature and high carbon content create reducing conditions. These coal mining by-products may be used as part of source control strategies. Based on laboratory tests, SRK (2016a) notes that the generation of selenium in blended / co-disposed mine rock and CCR is about three times higher than in mine rock alone.

Pit walls have low surface areas and are thought to be only minor sources of selenium. SRK (2016b) models exposed pit walls as very thin mine rock piles. Regardless, their selenium inputs are included in designs.

As noted above, historical underground workings seem unlikely to be a significant source of selenium, unless they provide inadvertent drainage conditions for in-pit mine rockpiles.

Sedimentation and holding pond landforms are key to water management. They are closely monitored to avoid selenium bioaccumulation.

4.0 CASE STUDIES

Table 7 provides a synopsis of observations from eight case studies based on publicly-available information. The observations are likely incomplete or may be slightly out of date, but the general findings are likely robust and provide a useful snapshot of the state of practice relating to selenium management in metallurgical coal mining.

Table 7. Case studies: Selenium management at Alberta and British Columbia coal mines

Name	Status	Observations
Cardinal River Teck Coal Hinton, AB	Closed	<ul style="list-style-type: none"> Elevated selenium due to historical mining practices Extensive watershed-scale research Pit Lake Bioreactor (Sphinx Lake) www.teck.com/operations/canada/legacy/cardinal-river/
Grand Cache CST Coal Grand Cache, AB	Suspended	<ul style="list-style-type: none"> Elevated selenium due to historical mining practices Extensive watershed-scale research End Pit Lake Bioreactor http://dx.doi.org/10.1007/s10230-014-0296-2
Grassy Mountain Riversdale Resources Blairmore, AB	Joint Review Panel (federal/provincial) EA* (pending), historical mine	<ul style="list-style-type: none"> No measured selenium impact from historical mining (mostly underground / minimal waste rock volumes) Optimized mine plan Unengineered covers Site selection for mine rock piles Collection and treatment of seepage from ex-pit mine rock Reliance on saturated mine rock backfill reactors Active water treatment as a contingency Site-specific water quality objectives proposed www.rivresources.com/site/Projects/grassy-mountain-project2/overview3
Tent Mountain Montem Crowsnest Pass, AB	Final terms of reference for EA*, historical mine	<ul style="list-style-type: none"> Elevated selenium levels due to historical mining Multiple lines of defence approach proposed Collection and treatment of seepage from ex-pit mine rock Reliance on saturated mine rock backfill reactors Ex-pit mine rock piles designed for source control Engineered wetlands www.montem-resources.com/projects/tent-mountain
Elk Valley Teck Coal Sparwood, BC	Four mines operating, one in care & maintenance	<ul style="list-style-type: none"> Elevated selenium due to historical mining practices Extensive watershed scale research Extensive prototype scale R&D on saturated mine rock backfill rockfills, cover system technology, internal structure Use of saturated mine rock backfill reactors Commercial-scale active water treatment Site-specific water quality objectives www.teck.com/responsibility/sustainability-topics/water/water-quality-in-the-elk-valley
Brule Mine Conuma Coal Tumbler Ridge, BC	Operating	<ul style="list-style-type: none"> Elevated selenium from rockpiles Operational, permitted biochemical reactor (Miller et al. 2019) www.miningnewsfeed.com/reports/annual/Brule_2017_Annual_Reclamation_Report.pdf

Name	Status	Observations
Michel Creek North Coal Sparwood, BC	Advanced (EA*)	<ul style="list-style-type: none"> • Semi-greenfields site, designed with selenium management as a central goal • Close work with Indigenous peoples and local communities • Receiving stream affected by elevated selenium from upstream mines • Extensive options analysis • Landform design for ex-pit rockpiles with multiple lines of defence • Reliance on saturated mine rock backfill reactors • Capture and treat • Active water treatment as a contingency <p>http://northcoal.ca/michel-coal-project</p>
Tenas Project Allegiance Coal Telkwa, BC	Advanced (EA*), historical mine	<ul style="list-style-type: none"> • Science-based environmental benchmark for selenium (site-specific objective) • Engineered ex-pit rockpiles <p>www.telkwacoal.com/site/the-project/project-overview</p>

*EA – environmental assessment process

These case studies indicate that:

- Selenium management is a central activity and is critical to the sustainability at coal mines in Alberta and British Columbia. Methods are evolving, and there is substantial publicly-available literature; there are often few details on results of technology development / field data
- Active and recently-closed (brownfield) open-pit mines typically have elevated selenium concentrations in downstream receiving environments due to leachates from historical mine rockpiles (where there are appreciable quantities of mine rock in the watershed)
- Mines are developing new techniques for selenium management with a focus on semi-passive systems, such as pit lakes and saturated mine rock backfill reactors. Most have plans to retrofit existing facilities for long-term passive, or semi-passive, treatment
- Plans at some proposed mines are affected by (predicted) elevated selenium concentrations in downstream receiving environments due to historical mining on other mine sites in upstream watersheds. Such mines are being designed in parallel with consideration of selenium management, with on-site monitoring programs and plans to develop semi-passive and potentially-active water treatments as contingencies
- Mines are generally not able to achieve the 2 µg/L water quality guidelines in downstream receiving environments, and consequently have developed (or are developing) site-specific water quality objectives
- No new mines have been constructed employing the entire new suite of technologies; all that are proposing to use them are in advanced EA / permitting stages.

There are also numerous other selenium management case studies available in the literature, including coal and metal mines in British Columbia. From the US, there are many case studies from mining and agricultural operations, many of which started before selenium was known to be an issue in Canadian Rocky Mountain coal mines. Appendix C provides links to some of these projects.

5.0 CONCLUSIONS

Selenium oxidation and leaching / transport from historic rockpiles has resulted in elevated selenium concentrations; these concentrations often exceed water quality guidelines in receiving environments at many Rocky Mountain coal mines in Alberta and British Columbia. Elevated selenium concentrations have the potential to affect downstream ecosystems, in particular, fish and aquatic birds. The problem has been recognized, and mitigation work is ongoing. Site-specific water quality objectives are being developed and established for many of these mines.

There has been considerable research and development and commercialization of selenium removal technologies. The industry has developed a solid understanding of the physical and biogeochemical processes related to selenium oxidation and transport, and a good understanding of the fate, effects, and chemical dynamics of selenium in aquatic receiving environments.

While there has been significant progress in the lab and at field scale with partial (but substantial) implementation of selenium management programs at several mines, selenium concentrations remain elevated in many receiving environments.

The two main strategies for selenium management are to employ a multiple-lines-of-defence approach (i.e., avoidance, source control, water management, and mitigation) following the observational method (a form of adaptive management with clear goals and objectives, designs for the most likely conditions, and pre-planned contingency measures should monitor performance fail to meet objectives), and timely adoption of contingencies.

Because only low selenium loads / concentrations can be released from mines without affecting downstream ecosystems and users, a large number of technologies need to be employed for each mine rockpile. Residual risks can be managed with effective decision making, design, construction / operation, monitoring, timely implementation of pre-planned contingencies, and regulatory / community oversight.

Numerous management strategies and technologies for selenium management are available, many at the commercial scale. That said, based on the publicly-available information available to the authors, few have been fully demonstrated at Rocky Mountain coal mines. Adoption and implementation need to proceed cautiously, and residual risks need to be managed closely. The sophistication of the design and operation of rockpiles will need to increase to a level similar to that used in earth-dam construction — a common activity at mines worldwide.

Liability for future performance related to selenium assessment and management rests not just with the mining company, but with regulatory agencies and local communities; therefore, these efforts should be managed jointly and transparently.

The most promising technologies are water diversion (“keeping clean water clean”), cover systems (to control ingress of water and oxygen into rockpiles), use of bottom-up construction and internal structures to limit gas transport and oxidation of mine rock, saturated mine rock

backfill reactors (SRFs) to immobilize selenium, and collection and active water treatment of contact waters with elevated selenium concentrations. There is considerable experience with these technologies (except for SRFs) internationally.

A number of proposed mines are in various stages of exploration, baseline studies, environmental assessment and permitting. For these mines, selenium management is a major environmental consideration. These projects are adapting plans and technologies to manage selenium. None of these projects has been fully permitted, and there is as yet no full-scale demonstration of these new technologies as an integrated system. Teck Coal is accumulating experience in designing and operating several technologies at full commercial scale — notably semi-passive SRFs, active water treatment, and a pit-lake bioreactor. Publicly-available data are insufficient to confirm whether these technologies can be considered proven technology.

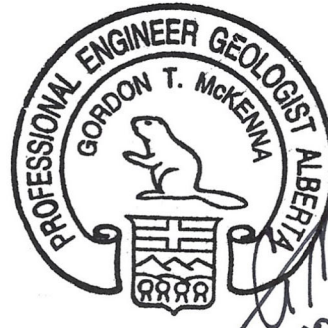
Mine proponents, Indigenous peoples, local communities, regulators, consultants, and academia are working to understand the behaviour of selenium, monitor and assess its impacts on the environment, and develop robust methods and strategies for selenium management for Rocky Mountain coal mines. There is an opportunity and a need for ongoing and closer collaboration.

6.0 IN CLOSING

Thank you for the opportunity to provide this review. The opinions expressed are those of the authors.



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Appendix A: About the authors

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Guy Gilron has 30 years of experience in ecotoxicology and ecological and human health risk assessment relating specifically to anthropogenic effects on aquatic and terrestrial ecosystems. Guy has expertise in the development, evaluation and application of water quality guidelines and criteria in numerous jurisdictions in North America and beyond.



Prior to his work as Principal, Borealis Environmental, he was VP Environment/Regulatory Affairs for Cardero Coal Ltd., and Director, Environmental Science for Teck Resources, based in Vancouver, BC, Canada. In the latter position, Guy contributed scientific input to the Elk Valley Selenium Task Force (EVSTF), a government/industry forum that addressed water quality issues and research in the Elk Valley. In addition to contributing to various research initiatives and several publications related to selenium risk assessment, including “Ecological Assessment of Selenium in the Aquatic Environment” (SETAC, 2010), Guy has played a key role in multi-stakeholder working groups related to selenium assessment, management, and treatment, specifically: the EVSTF; the Canadian Industry Selenium Working Group; the Alberta Selenium Working Group; the North American Metal Council Selenium Working Group; and, most recently, as Science Advisor to the Coal Association of Canada for the *CMER* multi-stakeholder consultations.

As part of a multi-year effort by the NAMC-SWG, Guy has served as the co-chair of a committee aimed at developing a contributed third-party CCME water quality guideline for selenium. He has been involved in a technical review of the Environment Canada and Health Canada Selenium Risk Assessment/Risk Management documents, and the draft USEPA water quality criterion for selenium, on behalf of the American Petroleum Institute and the NAMC-SWG.

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Gord McKenna is a geotechnical engineer and geologist who builds mining landforms and watersheds. He possesses over 30 years of experience in the mining industry in mine operations and as an international consultant for oil sands, coal, diamond, and metal mines, regulators, Indigenous peoples, and local communities. He is also an adjunct professor in the Civil and Environmental Engineering Department at the University of Alberta and the founding chair of the Landform Design Institute.



Gord and his teams have designed and built 23 reclaimed watersheds that cover 44 square kilometers and host 37 wetlands and 101 kilometres of streams. He has been a lead contributor to several manuals involving landform design, mine reclamation, and tailings, has co-authored 100 technical papers, and led over 40 landform design courses. He sits on eight geotechnical / tailings review boards across Canada.

Gord was a member of the Strategic Advisory Panel on Selenium Management (2010–2012) and has been involved with supporting research and designing mining landforms to manage selenium, working with numerous Rocky Mountain coal mines and local communities.

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McKENNA GEOTECHNICAL

Appendix B:

Environmental regulatory and permitting framework for the coal sector in Canada

General

Canada's coal mines operate within a relatively complex and stringent regulatory environment. The sector has the potential to be subject to up to 16 federal mining industry Acts and Regulations, many of which relate to coal mines, depending on site design, etc.; and, laws, regulations and permits at provincial and territorial levels.

The industry operates according to high reclamation standards, and provinces ensure that companies are legally responsible for reclaiming land disturbed by mining activities predominantly through environmental enforcement and security bonding.

Federal

The Canadian Environmental Assessment Agency (CEAA) regulates the *Canadian Environmental Assessment Act, 2012*. The CEAA and its regulations establish the legislative basis for the Federal practice of Environmental Assessment (EA) in most regions of Canada. The purpose of the CEAA is to protect components of the environment within federal legislative authority from significant adverse environmental effects caused by a designated project. The list below refers to considerations in a federal environmental assessment (EA) process (i.e., federal authorizations) and Section 5 environmental effects under the CEAA:

- potential impact on fish habitat, species at risk
- impingement on/proximity to, federal or First Nations lands
- involvement with cross-provincial or international transportation (e.g., ports)
- Federal authorizations (e.g., *Fisheries Act*, *Navigation Protection Act*, *Migratory Birds Convention Act*).

Federal EAs evaluate potential environmental effects of designated projects, including mine developments. The EAs comprise a pre-application phase (i.e., notification, development of terms of reference for the EA) and the submission and evaluation of the EA, culminating in the issuance (by the federal environment minister) of an environmental assessment certificate (EAC). The conditions established in the EAC provide a basis for the development and issuance of provincial mines permits, discussed below.

Provincial

Coal mining / production is currently regulated by provincial ministries of mines, environment, and natural resources. Once operating, coal mines are subject to provincial regulatory permits and approvals, including standards for mine effluent quality, established through provincial permitting / approval processes (Table 1). Provinces also require that receiving waters downstream of a mine site meet or address applicable ambient water quality guidelines. In some provinces (e.g., British Columbia), guidelines can be converted on a basin / watershed- or site-specific basis into water quality objectives (i.e., site-specific water quality objectives) to

address specific parameter issues, such as high background concentrations, lower targets to protect impaired systems, or cumulative impacts. These types of objectives are often specified in discharge permits, along with associated monitoring requirements. For example, coal mines are required to monitor downstream fish populations as part of their conditions for environmental approvals.

Site-specific permits / approvals are established based on the results of EAs for mitigation and monitoring. These conditions are specified in EACs, and / or *Mines Act* permits (BC) or *Responsible Energy Development Act* permits (Alberta). Provinces establish and publish guidance for setting “end-of-pipe” effluent discharge limits (Note: Alberta has incorporated loading considerations for selenium). These permits / approvals are updated as required, based on modifications to mining processes, volume processed, or expansion into various geographic/topographic locations, etc. Closure / post-closure / decommissioning activities and monitoring are also based on provincial permits related to site reclamation / remediation processes. Site-specific permits are established and negotiated based on provincial policy and requirements and are set out in mine-specific closure plans.

Appendix C:

Examples of selenium mitigative measures, treatment systems, and case studies

Surveys of selenium mitigation measures

- Treatment Technology Review (Golder Associates, 2020; commissioned by the North American Metal Council). <https://www.namc.org/docs/00300393.pdf>
- A Strategic Plan for the Management of Selenium at Teck Coal Operations (Swanson et al. 2010).
http://www.swansonenviro.ca/portfolio/SES_TeckStrategicAdvisoryPanelFinalReport2010.pdf
- Evaluation of Treatment Options to Reduce Water-Borne Selenium at Coal Mines in West-Central Alberta (Microbial Technologies, Inc.).
<https://open.alberta.ca/dataset/456eee9c-86d5-46e6-bc2e-e605c6599eba>
- Passive and semi-passive treatment alternatives for the bioremediation of selenium from mine waters (Martin et al. 2010).
<https://open.library.ubc.ca/cIRcle/collections/59367/items/1.0042571>

Selenium water treatment systems

- BQE Water Selen-IX System (BQE Water).
<https://www.bqewater.com/technology-solutions/selenium/>
- Treatment of Selenium-Containing Coal Mining Wastewater with Fluidized Bed Reactor Technology (Envirogen).
<https://www.envirogen.com/contaminants/selenium-water-treatment/#gref>
- ABMet System (General Electric)
<https://www.environmental-expert.com/downloads/abmet-brochure-423055>
- SeQuester (ChemTreat)
<https://www.watertechonline.com/wastewater/article/14176337/selenium-removal-from-industrial-wastewater>

Case studies regarding selenium mitigation measures and treatment technologies

- ABMet Case Study: GE Technology to Help Remove Toxic Metals from Wastewater at Canadian Coal Mine.
<https://www.ge.com/news/press-releases/ge-technology-help-remove-toxic-metals-wastewater-canadian-coal-mine>
- Constructed Wetland Case Study: Performance of the Operating Demonstration-Scale Constructed Wetland Treatment System at Minto Mine
<https://open.library.ubc.ca/cIRcle/collections/59367/items/1.0374546>
- Semi-Passive System Case Study: Biochemical Reactor System at the Brule Mine: a Semi-Passive Approach to Operational and Post-Closure Selenium and Nitrate Reduction.
<https://open.library.ubc.ca/cIRcle/collections/59367/items/1.0391938>

- Various Case Studies: *In Situ* Treatment of Mine Pools and Pit Lakes
https://www.itrcweb.org/miningwaste-guidance/to_insitu.htm
- Hybrid System (*In Situ*/Active) Case Study: Combining *in situ* treatment and active water treatment Case Study at Schwartzwalder uranium mine
<http://bc-mlard.ca/files/presentations/2016-24-HARRINGTON-combining-in-situ-active-water.pdf>

Appendix D: Technology readiness levels for selenium management for Rocky Mountain coal mines

Using a scale modified from NASA (2017), the selenium management technologies discussed in the review are subjectively scored. Table D-1 presents the scoring definitions; Table D-2 presents the descriptions and scores. Results are presented graphically in Section 3.2 (Table 4).

Table D-1. Technology readiness level (TRL) descriptions

Level	PHASE	NASA (2017) description	COAL mine selenium adaptation (with indicative dimensions as a guide)
TRL 1	Research	Basic principles observed and reported. Basic scientific research that can be turned into an application or a concept under a research and development program is considered. Examples might include paper studies of a technology's basic properties.	Concept or idea described in a paragraph.
TRL 2		Technology concept or application formulated. An idea is proposed for the practical application of current research, but there are no experimental proofs or studies to support the idea. Examples are limited to analytic studies.	Paper study, literature review, technology assessment, perhaps index tests.
TRL 3		Concept or application proven through analysis and experimentation. Active research and development begins, including analytical laboratory-based studies to validate the initial idea, providing an initial "proof of concept." Examples include components that are not yet integrated or representative.	Lab bench scale. Volume < 0.01 m ³ (10L) Area < 1 m ² Depth < 0.2 m Progress report
TRL 4		Basic prototype validated in laboratory environment. Basic examples of the proposed technology are built and put together for testing to offer an initial vote of confidence for continued development. Examples include integration of "ad hoc" hardware in the laboratory.	Lab pilot scale (batch or continuous). May include field barrel test or small mesocosm. V = 1 m ³ A = 2 m ² D = 1 m Full R&D report
TRL 5	Development	Basic prototype validated in relevant environment. More realistic versions of the proposed technology are tested in real-world or near real-world conditions, which includes initial integration at some level with other operational systems. Examples include "high-fidelity" laboratory integration of components.	Small field pilot with highly controlled conditions over hours or a few days. "Minivan-sized" field test V = 200 m ³ A = 100 m ² D = 3 m Full R&D report

Level	PHASE	NASA (2017) description	COAL mine selenium adaptation (with indicative dimensions as a guide)
TRL 6		System or subsystem model or prototype demonstrated in a relevant environment. A near final version of the technology in which additional design changes are likely is tested in real-life conditions. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Large field pilot with several variables run over weeks or months. Large (>20 to 30m high) field pilot or well-characterized / monitored rockpile $V = 10^6 \text{ m}^3$ $A = 5 \text{ ha (50,000 m}^2\text{)}$ $D = 30 \text{ m}$ R&D report.
TRL 7		System prototype demonstrated in a relevant environment. The final prototype of the technology that is as close to the operational version as possible at this stage is tested in real-life conditions (e.g., in an aircraft, in a vehicle, or in space). [Note for mining that some TRL 7 commercial technologies fail after full-scale implementation and are abandoned].	Field prototype run at commercial scale and rates under favourable conditions or well characterized / monitoring rockpile $V > 10^6 \text{ m}^3$ $A = 100 \text{ ha}$ $D = 50 \text{ m}$ Full landform design, as-built, and R&D report
TRL 8	Commercial	Actual system completed and qualified for flight through test and demonstration. The technology is thoroughly tested and no further major development of the technology is required. Its operation as intended is demonstrated without significant design problems. [For selenium management, TRL 8 and 9 may be considered "proven technology."]	In commercial use at one site, significant improvements still likely. $V = 10^8 \text{ m}^3$ $A = 100 \text{ ha}$ $D = 150 \text{ m}$ Full landform design and as-built and annual performance reports
TRL 9		Actual system proven through successful operation. The final operational version of the technology is thoroughly demonstrated through normal operations, with only minor problems needing to be fixed. Any further improvements to the technology at this point, whether planned or not, will be treated as a TRL 1. Examples include testing the system under operational mission conditions.	Common commercial technology used at multiple sites; only minor improvements expected (continuous improvement phase). Ditto but $V > 10^8 \text{ m}^3$ $A > 1000 \text{ ha}$ $D > 50 \text{ m}$ Full landform design and as-built and annual performance reports

Note that the scoring is based on publicly available information (based on references cited in this report) for Canadian Rocky Mountain coal mines. In some cases, technology readiness levels are higher for other mining applications (e.g., control of acid rock drainage), in different climates and jurisdictions (e.g., selenium biochemical reactors in the United States), or for various components of a technology (e.g. mine rock pile construction).

Also note that pilot and prototype scales for mining technologies are typically much larger than that for commercial water-treatment technologies.

There is no standard for determining which technologies are *proven technologies*. However, descriptions of proven technology typically echo several of the following themes:

- The technology is technically feasible and cost-effective to use
- The technology is available for implementation without further significant R&D efforts or delays – it is “off-the shelf”
- Components of the technology are commercially proven
- The scientific basis behind the technology is well understood
- The technology is easy to construct and maintain
- The technology has long-term widespread use, tried and true, with a track record of implementation
- There is a high level of confidence that the technology can deliver what is promised
- Reliable in design
- “Low risk”
- The technology is economical, and a contractor would be able to guarantee performance with a price guarantee, and the technology was “bankable” – financing would be available. Capital and operating costs can be estimated to within say 10 to 15 percent.

Table D-2. TRL Scoring and notes

Type	Technology	TRL for selenium management	Notes
Mining methods	Underground mining	4	Underground mining is a common technology. While ARD from underground workings elsewhere is common, underground mining is likely to avoid high selenium loads. SRK (2016b) reports up to 10 ppb Se from historic underground workings at Grassy Mtn property. Underground mining typically produces only small volumes of mine rock (a major source of selenium in coal mining). <u>Potential next steps to raise TRL:</u> Compilation of regional historical experience and seepage water quality data. Estimates of mine rock volume factors for underground mining operations. It seems likely with modest effort, this technology could be upgraded to TRL=7. That said, underground mining for the proposed rates of coal production is likely uneconomical at most mines.
	Selective mining	8	Simple and straightforward but not all mines have sedimentary bedrock units that are significantly higher or lower in selenium. Ryan and Dittrick (2001) describe selenium occurrences in units of the Mist Mountain Formation.
	Selective handling	7	Selective handling and co-disposal of CCR and tailings are common. CCR and tailings show evidence of microbial reduction that limit selenium release (SAPSM 2010). SRK (2016a) reports lab studies of co-disposed rejects and rockpile material increases selenium production by a factor of 3. <u>Potential next steps to raise TRL:</u> Analysis of available data. Field trial.
Source control in mine rock piles	Siting mine rockpiles	8	There are only limited options for siting mine rockpiles at most mines, but there is a reasonable understanding guiding good practice. Minimizing the aerial extent of out-of-pit mine rockpiles is indicated. The main strategy is to limit the “sprawl” (CCA 2015) of mine rock placement, selecting locations with low permeability bedrock, and avoiding placing small volumes of mine rock into “new” watersheds.
	Foundation preparation	7	Foundation prep for ex-pit rockpiles is common for geotechnical reasons, and would be straightforward to reduce the potential for seepage into surficial and bedrock aquifers if practicable. <u>Potential next steps to raise TRL:</u> better hydrogeologic characterization of each proposed mine rockpile and pit lake site conditions.
	Controlling internal structure	7	The internal structure of end-dumped rockpiles and the impact on oxidation is well understood in coal and metal mines (e.g., Smith et al. 1995; Azam et al. 2006). The benefits of controlling gas transport are well known (Meiers et al. 2018) and practicable to implement, but the efficacy for controlling selenium has not been demonstrated at full scale. SAPSM (2010) and Claridge et al. (2012) provide additional methods for building mine rock piles to control selenium. <u>Potential next steps to raise TRL:</u> The current state of practice would be improved with better hydrogeologic characterization of each proposed mine rockpile.

Type	Technology	TRL for selenium management	Notes
	Controlling bacteria (temporary)	7	The use of bactericides showed promise in the 1990s (e.g., Parisi et al. 1994) but was found to have only short-term effects -- the microbial communities quickly adapt (Loos et al. 1989; INAP 2014). Not recommended except for short term conditions.
	Cover systems	7	The use of cover systems to control net percolation of water is common worldwide (INAP 2017) but is less common, to limit oxygen ingress (Wels et al. 2003; Bain et al 2016). Covers are in use at Teck's Cheviot and Cardinal River mines. <u>Potential next steps to raise TRL:</u> Further cover trials and publications. Teck is conducting a very large geosynthetic cover trial at its Greenhills Mine (Teck 2020).
	Blending mine mines / co-disposal	7	Blending of mine wastes to manage oxidation is becoming more common at metal mines including blending of mine rock and paste tailings (Williams 1998; Wilson et al. 2006). The coal mines commonly blend coarse coal reject and tailings for co-disposal which can result in deposits with low oxygen / low selenium production (Siddique et al. 2007). <u>Potential next steps to raise TRL:</u> Full-scale field trials.
	Add reducing agents Enhanced microbial reduction	4	A common active water treatment technology (Golder 2020), and common for biochemical reactors, but not proven at mine rockpile scales. Use of carbon sources to enhance bacterial action in saturated mine rock backfill reactors is proposed (e.g. Benga Mining 2020). <u>Potential next steps to raise TRL:</u> Pilots and prototype trials, injection and monitoring of commercial-scale deposits.
	Submergence	8	Submergence of mine rock is a common technique for controlling acid rock drainage by limiting oxygen (e.g. INAP 2014) at many mines. See also saturated rock backfill technology below.
	Schedule and timing	4	Delays in "going acid" commonly seen and taken advantage of in metal mines with acid generating materials (INAP 2014) and evident in lab testing of coal mine rock (e.g. SRK 2016a) but not demonstrated in the field. More useful is acceleration of construction of mine rock fills to limit oxidation products that form during construction. <u>Potential next steps to raise TRL:</u> Close monitoring of oxidation of new mine rock piles or prototypes during construction.
Water management	Understanding baseline conditions	8	Characterization of baseline conditions common for all modern mines. It is difficult to estimate baseline conditions for historic or old mines. Wellen et al. (2018) provide a useful framework.
	Diversions	9	Use of diversions in mining including Rocky Mountain coal mining is common practice and essentially a heavy-civil application.
	Covers to shed water	4	Covers to shed water are common practice internationally (INAP 2014, 2017) but have yet to be employed at Rocky Mountain coal mines. <u>Potential next steps to raise TRL:</u> Teck (2020) is designing a large (200-hectare) geosynthetic cover prototype.

Type	Technology	TRL for selenium management	Notes
	Lotic discharge	9	Discharge into flowing streams (bypassing wetlands) is simply a matter of extending pipelines or constructed creeks.
	Rock drains	9	Use of rock drains is common in the Rocky Mountain coal mines (Piteau 1997).
	Surface water hydrology	8	Designing and constructing systems for surface contact-water hydrology / management is routine in the Rocky Mountain coal mines and essentially a heavy-civil application.
	Managing seepage and groundwater	8	Actively managing groundwater is a common commercial activity elsewhere. Pit dewatering is a common activity (e.g. Teck 2014).
Mitigation	Surface and groundwater collection	6	Collection is mainly through the use of interception ditches and wells, and in some cases cutoff walls. Surface water collection at the toes of mine rockpiles is common, but no evidence of groundwater interception wells was found. Bypass flow is a concern (see Barlow et al 2018). <u>Potential next steps to raise TRL:</u> Monitoring of commercial use as needed.
	Saturated mine rock backfill reactor	7	Teck Coal is constructing several saturated rock backfill reactors at commercial scale (Teck 2021) and has been researching and monitoring the results of unengineered reactors for 10 years. Bianchin et al. (2013) report results from a northeast BC coalmine saturated backfill. <u>Potential next steps to raise TRL:</u> Ongoing monitoring and assessment.
	Biochemical reactors	7	Large semi-commercial pilots have been successfully employed in other industry (see Table 5 this report). Nkansah-Boadu (2019) describes the selenium reduction performance of marsh wetlands at a BC coal mine. Teck (2015) describes a biochemical reactor (Leyland Pond) at its Cardinal River operation. <u>Potential next steps to raise TRL:</u> Pilot and prototype reactors, especially semi-passive underground reactors.
	Pit lakes	7	Sphinx Lake is a pit lake being used to manage selenium (Brinker et al. 2011) <u>Potential next steps to raise TRL:</u> Ongoing monitoring and experience.
	Active water treatment	7	Various technologies have been employed for active water treatment at Rocky Mountain Coal Mines (Golder 2020; Teck 2020; Table 6 this report). <u>Potential next steps to raise TRL:</u> Ongoing monitoring and experience.
Note: This table is based on information in the references list in this report. There may be additional data yet to be published or not found by the authors that may allow the TRLs to be revisited, and indeed one would expect the technology readiness level to increase over time as more field experience is gained. Note that in the mining industry, many new technologies operating at TRL=7 fail to deliver the promised results, and are ultimately discarded (e.g. McKenna et al. 2011; CTMC 2012).			